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REGIONAL FREQUENCY DISTRIBUTIONS OF MIXING DEPTH PARAMETERS IN CANADA: A CLIMATOLOGICAL STUDY OF AIR POLLUTION POTENTIAL

E. WILSON
AIR QUALITY ASSESSMENT SECTION

REPORT ARQN-3-79 JULY 1979

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This is one of a series of internal reports prepared by the Air Quality Assessment Section of the Atmospheric Dispersion Division.

The views expressed in this document reflect the opinion of the individual contributors and do not necessarily portray the official position of the Air Quality and Inter-Environmental Research Branch or the Atmospheric Environment Service.

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PREFACE

Demands on the Atmospheric Environment Service to deal with current and future environmental issues have focused considerable interest on the lower atmosphere and the physical processes that occur there. There is an increasing requirement for information about these processes upon which important environmental decisions can be based.

Over the past decade, various efforts have been made to compile statistics on the behavior of the lowest layer of the atmosphere in which pollution is generated and dispersed. Unfortunately, there is no simple technique or network available to adequately measure these atmospheric processes in the boundary layer where considerable variability of measurable parameters occurs in time and space. Limitations in the available data and measurement techniques are recognized and continue to be a major problem in the pursuit of climatological information about this layer.

This report is a complementary one in a series of Air Pollution Potential Studies of Canada undertaken by the Atmospheric Environment Service. The purpose of the study is to provide additional information (within the limits of the data available) to aid in environmental assessments in Canada.

ABSTRACT

In an effort to define the behavior of the lowest 1000 m of the atmosphere in the transport and dispersion of pollutants, the synoptic-scale climatologies of various pollution potential indices have been compiled and analyzed over the past ten years.

The following report is one such study of the Air Pollution Potential Climatology of Canada, and uses a similar data base to the previous studies, (Munn, 1970; Portelli, 1977). The current study examines the percentage frequency of occurrence of specified ranges of the three mixing depth parameters: (1) maximum (afternoon) mixing heights, (2) mean transport wind speeds through the mixed layer, and (3) ventilation coefficients, for over 33 Canadian and 13 U.S. border rawinsonde stations for the period July 1965 to June 1969.

Through a comparison of the frequency patterns with previous pollution potential studies conducted in Canada and the U.S., it was possible to identify twelve regions across Canada with similar seasonal frequency distributions and meteorological/topographical characteristics.

The mean statistics over each region are examined in terms of related synoptic-scale (or mesoscale) climatological controls. Qualitative estimates of conditions over the region are summarized for each season.

SUMMARY AND CONCLUSIONS

SUMMARY AND CONCLUSIONS

The following sections summarize the results of the study and describe the regions and synoptic situations across Canada in which limited dispersal conditions occur most frequently. These conditions are readily identified in Table I which gives the average seasonal frequencies of ventilation coefficients less than 6000 m^2/s for each region. Values of ventilation coefficients which do not exceed 6000 m^2/s are condsidered indicative of high air pollution potential by the U.S. air pollution forecast program (Stackpole, 1967; Gross, 1970). A comparable Canadian "threshold" value has yet to be determined and is currently under review.

TABLE I: Seasonal Percentage Frequency Distribution of Ventilation Coefficients Less Than 6000 m^2/s.

		Spring	Summer	Fall	Winter
1.	Pacific	65.3*	83.3*	91.3*	87.5*
2.	Rockies	37.7	26.1	68.1*	92.9*
3.	Lee Rockies	37.2	23.9	50.4	88.2*
4.	Prairies	49.7	35.4	62.8*	96.5*
5.	Great Lakes	42.9	39.0	55.0	82.7*
6.	Appalachians	32.6	27.8	48.0	71.6*
7.	Atlantic	69.8*	81.0*	66.4*	70.1*
8.	Quebec-Lab	51.2	34.5	63.3*	88.9*
9.	Mackenzie V.	75.0*	51.2	87.9*	99.2*
10.	Hudson Bay	77.5*	58.9*	77.8*	95.9*
11.	Baffin	85.6*	70.2*	83.4*	96.7*
12.	High Arctic	96.5*	92.1*	95.7*	100.0*

* - around 60% of the cases or more are below 6000 m^2/s

In general, the ventilation coefficient climatology of Canada (Portelli, 1977) indicates that much of the country has values less than 6000 m^2/s. In Table I, over 70% of the winter cases in all regions are in this limited diffusion range. To assist in establishing seasonal differences and to enable regional comparisons, however, this value has been used as a relative indicator with the following results.

1. Regions North of 60°N

The regions mainly north of latitude 60°N include the High Arctic, Baffin, Mackenzie Valley and Hudson Bay. These regions have the most frequent conditions of limited diffusion on an average annual basis. The episodes of restricted mixing in the boundary layer are particularily evident in the fall, winter and spring. An average of over 75% of the cases in each region have ventilation coefficients less than 6000 m^2/s (Table I) during this period. (Over 95% of the winter cases in these regions are in this limited range).

The main physical and meteorological factors that contribute to these high frequencies include:

(1) The quasi-continuous snow and ice cover from the late fall to the early spring.

(2) The direct path for unmodified cold Arctic air to penetrate from the Arctic Ocean source region.

(3) The limited incoming solar radiation. (The Polar Night from late fall to early spring shrouds most of the regions in total darkness during that time.)

Surface or near surface-based radiation inversions and severely restricted horizontal and vertical mixing may persist for long periods, trapping pollutants and resulting in high local concentrations.

The factors that relieve these periods of stagnating conditions and aid in the reduction of high levels of pollutants in these regions include:

(1) Surface heating: (a) diabatic heating over open water, (b)thermal energy from developed areas, and (c) more direct and longer hours of sunlight.

(2) Moderate to strong surface and upper wind patterns: (a) subsidence flows to the lee of ranges, (b) warm advection flows from milder latitudes or open water, (c) cold advection flows that increase turbulent mixing in the boundary layer, and (d) convergent or divergent flows.

(3) Variable surface characteristics: (a) uniform terrain that permits stronger gradient winds to develop, (b) thermal properties of an extensive snow-free dark forest cover.

(4) Cyclonic development: provides unstable lapse rates and greater low-level turbulent mixing along the secondary storm tracks of the north.

The study of the 'Frequency of Surface-Based Inversion in Canada' (Munn et al, 1970) concluded that the Arctic in the winter has the most serious pollution potential. A comparison of their report with the current study shows rather good agreement in the seasonal frequency distributions. The percentage frequency of surface-based inversions and the percentage frequency of mixing heights less than 200 m, for example, give similar results.

The earlier report has winter frequencies of 60-80% in the Eastern Arctic. (Baffin = 62.2% and the High Arctic = 83.8% in the current report). Similarily, the Mackenzie Valley has 50-65% (compared to 59.3%).

2. Maritime Regions

The five major maritime regions includes the Atlantic, Pacific, and in the summer the Hudson Bay, Baffin and High Arctic regions. These marine areas of Canada encounter serious pollution potential problems at all times of the year. Over 60% of the cases are below 6000 m^2/s in any of these regions throughout the year (Table I). (In the winter, over 70% of the cases are below this value).

The Atlantic and Pacific maritime regions, however, are of particular interest for the following reasons:

(1) Both regions border major oceans. The Pacific Ocean is the largest ocean in the world and covers an area greater than the combined area of all the continents. The oceans are salt water bodies and bordering coastal areas rarely freeze in the winter with the exception of the Gulf of St. Lawrence and the Labrador coast north of Newfoundland.

(2) Both coastal climates are influenced by major cold and warm water ocean currents.

(3) The Atlantic region is located along the lowest latitude belt in Canada. The Pacific region is located along the most southern latitude belt in western Canada.

(4) Both regions support a much larger population than the other maritime regions of Canada.

(5) The major fishing, forestry and mining industries in Canada are found along these coasts.

(6) Many industries favour coastal sites for their operations.

(7) During the principal growing season, when plants are particularly vulnerable to high levels of pollutants, the frequencies of ventilation coefficients below 6000 m^2/s are over 80% in both regions (Table I). This constitutes the highest annual frequency for the Atlantic region.

Fall and Winter Conditions

The northern three major maritime regions have been described from fall to spring in the previous section. At the open coastal regions further south, the fall through winter months have extensive cloud and precipitation. For example, the wet season begins late in September and ends about the middle of March along the West Coast. Maximum evaporation and drastically reduced insolation occurs. As a result, afternoon mixing heights along the coast are reduced in spite of the low-level instability generated by the colder airmasses traversing the relatively milder open waters.

Spring and Summer Conditions

In the spring and summer, other factors reduce the maximum afternoon mixing heights and in some cases severely in these major maritime regions. These include:

(a) The marine inversion: Warm airmasses override the cooler air that has been modified over the relatively colder open water and produces an often pronounced surface-based inversion.

(b) The underlying surface: Ice-flows, permanent glacial ridges, the cold Labrador current, Pacific upwelling, etc. increase the thermal differential of the above process.

(c) The over-riding airmass: Incidences of temperature and moisture advection from the humid southern latitudes or of hot, dry air from the heated continental airmasses also increase the thermal differential in the boundary layer over the open water. Fog, stratus, and a stably stratified layer are

commonplace in the mid-latitude high pressure cells that build along the Atlantic and Pacific coast during the summer.

(d) The sea-breeze circulation: This onshore wind will carry the inversion and marine stratum from over the water inland by the afternoon and thereby reduce surface temperatures and corresponding maximum mixing heights over the land.

From the foregoing statistics and observations, it may be concluded that the five major maritime regions pose the most serious pollution potential problems on a year-round basis. During the summer, these incidences of high pollution potential may present a serious hazard to sensitive receptors if combined with emissions from regional sources. For this reason and those cited earlier, particular attention must be given to these regions with the recommendation that further studies be undertaken.

3. Interior Continental Regions (S of 60^{o}N)

Between the Western Cordillera and the much lower highlands of the Eastern Cordillera, a broad and relatively flat corridor extends from the Arctic Ocean, through the central U.S. to the Gulf of Mexico. Airmasses move virtually unrestricted from the north or the south. As a result, drastic weather changes occur through the mid-latitude belt and especially over interior continental regions south of latitude 60^{o}N which include the Prairies, Lee of the Rockies and Central Quebec. Corresponding seasonal variations are evident in the mixing depth frequency patterns across these regions.

For example, the spring and summer frequencies of ventilation coefficients less than 6000 m^{2}/s (Table I) average around 50% and 35%, respectively, for both the Prairies and the Laurentian Highlands. In the fall and winter, a significant change takes place. Fall frequencies of over 60% increase to over 88% in the winter. In the Prairies, over 96% of the winter cases fall in this critical range.

In addition to the direct access of the unmodified Arctic air, a number of other factors make the winter cases more severely restricted in these regions:

(1) The cold, stagnating anticyclone is established across the Prairies from late fall to early spring.

(2) A quasi-continuous, highly reflective snow cover is present over the regions.

(3) Long, clear nights are followed by a relatively low sun-angle during the day. Radiation inversions are not as readily modified.

4. Mountainous Regions

These regions include the rugged terrain and deep valleys of the Western Cordillera and to a lesser extent, the Appalachians to the east (i.e., the Rockies and Appalachians Regions).

In the Rockies, over 68% of the fall cases and over 92% of the winter cases have ventilation coefficients less than 6000 m^2/s* (Table I). These incidences of high pollution potential are the result of:

(1) Cold air drainage into the valley.
(2) Trapping of cold Arctic airmasses that break through the Divide.
(3) Nocturnal radiation inversions that do not readily "burn-off" at lower elevations in the region.
(4) Deep snow accumulations.

The above effects in mountainous terrain are much less extreme in the Eastern Cordillera due to the considerably lower elevations, the southern latitude and the modification by the Atlantic and the longer path for Arctic air.

5. Lee of the Rockies

The major subsidence zone to the lee of the Western Cordillera is found in the Lee of the Rockies region. Other areas with similar characteristics include (a) the lee of the Coast Range in southern B.C. and to a lesser extent (b) the southwestern Mackenzie Valley. Lack of upper-air data limit the study in these areas.

From spring to fall, the region across southern and central Alberta (see Fig. II) has one of the lowest frequencies of ventilation coefficients less than 6000 m^2/s. At the same time, frequencies of ventilation coefficients greater than 11,000 m^2/s are the highest in all of Canada. These results suggest that optimum diffusion conditions for Canada occur to the lee of the Rockies at this time.

Several factors are responsible for these favourable conditions. In the summer, intense heating of the rolling prairie grassland produces convective currents and dry thermals that raise the afternoon mixing heights and maintain constant motion in the lower atmosphere. During the transition seasons, the upper flow shifts from (or to) the mean northwesterly flow of winter to (or from) a mean westerly subsiding flow in the spring (or fall). Warming and drying of the descending Pacific airmasses provide less cloud, greater surface heating and convective mixing, less snow cover and stronger mean surface winds - especially along the "Chinook Belt".

In the winter, however, a major change occurs. The Arctic high pressure ridge extends through the prairies and the cold, stable Arctic airmass is firmly established against the mountains. Over 88% of the cases have ventilation coefficients less than 6000 m^2/s at this time.

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* It should be noted that many industrial sites are located along the river valleys where some of these effects are most pronounced. Because the rawinsonde stations are located at slightly higher elevations, the frequency of low mixing heights compiled for the region are likely underestimated for these sites.

Periodically, lee cyclogensis will allow modified Pacific air and strong winds to surface across southern sections of the region and relieve these stagnating winter conditions. For this reason, the southern half of the region experiences a lower frequency of limited mixing episodes than the north. Moreover, the impact of the lee subsidence decreases with the distance east of the divide and the elevation of the mountains over which the airmass descends. (The area along the foothills south of Red Deer to Lethbridge experiences the greatest frequency of "chinooks".)

At slightly higher latitudes in the region, additional factors such as the lower sun-angle, the more persistent snow cover and the extensive friction-inducing forest vegetation compound the periods of stagnation. When warmer faster moving airmasses do reach these areas, they usually override the cold surface layer. Pronounced surface-based inversions may persist for weeks, trapping pollutants and giving high local concentrations. These are significant variations within the region because the northern half has the major heavy industrial activity with numerous oil refineries, sour gas plants, etc. (at Edmonton and Fort McMurray, for example).

6. Great Lakes Region

The Great Lakes Region is a southern interior modified continental - industrial region. Relative to most of the other regions in Canada, the Great Lakes region has less frequent incidences of limited mixing throughout the year (Table I).

There are several main reasons for this:

(1) The region has a large, relatively homogeneous surface.

(2) It is located in the most southern latitude belt in Canada.

(3) The modifying influence of the large, open water bodies reduces the severity of stagnating conditions from late fall to early spring.

(4) It is located along the main storm strack in the mid-latitudes. Constantly interchanging airmasses and synoptic activity reduce periods of stagnation throughout the year.

(5) Land and lake-breeze circulations ensure almost continuous interaction in the boundary layer along the coastal sites throughout the year.

The "mixing depth" statistics refer to the meteorological pollution potential of a region. Other factors may make an area pollution prone. For instance, the highest density of industrial activity and the largest population centres in North America are found around the Great Lakes. This makes the areas particularly around the lower Great Lakes vulnerable to high pollutant concentrations at certain times of the year and in conducive synoptic situations.

In conclusion, high pollution potential conditions in Canada occur most frequently in the following locations:

(1) The regions north of latitude 60^{o}N - all year.*

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* Note: The mixing depth computational procedure is most applicable to mid-latitudes and has yet to be tested out at higher latitudes in Canada.

(2) The five major martime regions - spring and summer.
(3) The plains - fall and winter.
(4) Rugged terrain - fall and winter.
(5) Industrial zones (especially in a coastal environment) - all year.

Although high frequencies of limited mixing conditions occur in the fall and winter in all regions of Canada, the impact of high concentrations of pollutants would be most serious in the spring and summer growing seasons. In this case, the major marine areas of Canada including the Atlantic and Pacific coastal regions pose the greatest concern and require further examination.

INTRODUCTION

INTRODUCTION

The following report deals with regional air pollution potential in Canada. It is a climatological study based on the percentage frequency of occurrence of three 'mixing-depth' parameters: afternoon (maximum) mixing height, mean wind speed through this mixed layer and ventilation coefficient.

OVERVIEW

To expand on the concept of 'pollution potential' and 'mixing depth', several questions may be asked.

a) What role does the atmosphere play in the transport and diffusion processes of air-borne pollutants?

Pollution emitted into the atmosphere at the surface is diluted as it expands into larger and larger volumes of air. The amount of air available to a region to reduce the concentration of pollutants depends on a number of interrelated meteorological and topographical factors.

In this respect, air pollution potential has been defined (Munn et al, 1970) as the meteorological conditions conducive to the occurrence of high concentrations of pollutants, given the existence of strong sources. High pollution potential exists when certain meteorological elements or their combination would produce poor air quality with the introduction of pollutants.

b) What are the meteorological conditions that alter atmospheric pollutant concentrations?

In the transport and dispersion stages of the air pollution cycle the diffusion of pollutants released into the atmosphere at or near the surface are controlled by turbulent motions in the boundary layer. Pollution problems over a region arise when the amount of pollutant injected into the atmosphere exceeds both the sink strengths and transport terms.

High/low air pollution potential is determined by the(i) horizontal and vertical motion of the lower atmosphere which transports and dilutes pollutants,(ii) trajectories from clean air reservoirs, (iii) precipitation scavenging processes*, and (iv) persistence of the above conditions that may have a cumulative effect on pollutant dispersion.

c) What meteorological parameters best describe and are available to document some of these processes?

The most serious pollution problems occur at times when horizontal and vertical mixing are severely restricted and trajectories from clean air reservoirs do not occur for an extended period.

The horizontal and vertical mixing through the atmosphere near the surface can be determined from the wind and temperature stratification in the boundary layer. The upper limit of vertical diffusion is normally taken as the 'mixing height', i.e., the level at which mixing is topped by a stable layer. The mean transport wind speed through the mixing layer (Miller, 1967; Holzworth, 1967) is a measure of the horizontal diffusion.

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* NOTE: After a period of rain, air quality improves as a result of 'washout or rainout' of pollutants.

Atmospheric stability and wind shear through the lowest layers of the atmosphere are observed by upper-air soundings. A rawinsonde network of upper-air stations routinely provides information about the vertical structure of the atmosphere twice daily at 1200 GMT and 0000 GMT. However, limitations in the spatial density of the network and technical complications (see Appendix D) render difficulties in the climatological documentation of boundary layer processes. In spite of these limitations, rawinsonde data do provide valuable information about boundary layer processes and a consistent base from which to compare these processes across all regions of Canada.

Other indicators of horizontal diffusion are the strength and persistence of surface winds. The denser network and longer period of data of the surface stations reporting wind speed are the advantages of using surface-based wind speed data as a climatological indice of pollution potential. Unfortunately, certain factors limit its applicability. Large variations in this parameter may occur over small horizontal distances and in variable terrain due to frictional interactions. Also, pollution sources often emit well above the surface.

Two factors that tend to increase air pollution concentrations are light low-level winds and a stable atmosphere. High pressure systems or anticyclones are characterized by both of the above features. Thus, the synoptic climatology of stagnating anticyclones provides useful information about the frequency and intensity of major air pollution episodes. Mean surface and upper level pressure charts reveal average positions of cyclones and anticyclones over a region on a seasonal basis. Similarily, major storm tracks provide information about sources, trajectories and frequency of exchange of airmasses over a region.

The effects of precipitation washout/rainout processes on regional pollution levels are difficult to isolate from the frontal activity and airmass exchanges frequently accompanying large-scale rainfall. Regions of heavy rainfall due to topographical influences (for example, windward side of a mountain range) also experience low-level turbulent mixing as the airmasses converge against the barrier. Most of these processes tend to improve the air quality of the affected area. However, they are difficult to relate to a single observed meteorological parameter.

d) What climatological indices of air pollution potential have been examined in North America?

Numerous local studies of pollution potential have been conducted in the United States and Canada over recent years. Regional-scale studies, however, are more readily summarized and relate to the current study.

National studies covering the contiguous United States include: the low-level inversion frequency (Hosler, 1961), estimates of mean maximum mixing depths (Holzworth, 1964), the synoptic climatology of stagnating anticyclones east of the Rocky Mountains (Korshover, 1967), mixing heights, wind speeds and potential for urban air pollution (Holzworth, 1972), meteorological episodes of slowest dilution (Holzworth, 1974), and climatological data on atmospheric stability (Holzworth, 1974).

In Canada, air pollution potential studies were initiated by Munn et al (1970). In this study, the frequency of ground-based inversions was compiled from data (00Z and 12Z) from Canadian network rawinsonde stations for the period July 1965 to June 1968, inclusive. (Selected tower data was

also used). Temperatures at the surface and the first significant level above the surface were compared. A rawinsonde surface-based inversion occurs when air at the first significant level above 10 mb (about 80 m) above the surface is warmer than the surface air temperature. (Upper-air data below this level is considered unreliable. See Appendix D). The results include regional estimates of day and night surface-based inversion frequencies for each season. A qualitative summary of the inversion climatology is provided for eight regions across Canada.

In 1972, Shaw et al examined the persistence of light surface winds using data from 111 Canadian synoptic and aviation weather stations during 1957 to 1966. The number of occurrences in two persistence classes (i.e., 24 - 27 hours and greater than 48 hours) were prepared for each season. The report identifies various regions in Canada (and seasons) that have the greatest frequency in both classes.

A third synoptic-scale report (Portelli, 1977) examined the mean mixing heights, mean transport wind speeds through the mixed layer and the ventilation coefficients for Canada. These analyses used rawinsonde data from 33 Canadian and 13 northern U.S. stations for the period from July 1965 to June 1969, inclusive.

SOURCES OF DATA

The current report uses the identical data set as that used in the latter study. The percentage frequency of occurrence of the three mixing depth parameters have been compiled and tabulated for each of the 46 rawinsonde stations available for the studies. Further details and a description of these data sets are found in the report, "Frequency Distributions of Mixing Depth Parameters in Canada" (Portelli and Wilson, 1979).

PROCEDURE

(i) The Mixing Depth Concept: When doing air pollution assessments, it is important to know the extent of vertical mixing through the boundary layer. This level is normally a maximum during the afternoon when diurnal insolation peaks.

The 'mixing depth' concept (Holzworth, 1967) is founded on the principle that heat transferred to the atmosphere at the earth's surface results in convection, vertical mixing and the establishment of a dry adiabatic lapse rate. The maximum (afternoon) mixing height is calculated as the height above ground at which the dry adiabatic extension from the maximum surface temperature intersects the vertical temperature profile observed at 1200 GMT (Fig. I). The maximum surface temperature is determined from observations taken during the LST periods listed by Portelli (1977).

The major assumption of the mixing depth method is that changes in the vertical temperature structure between 1200 GMT and the local surface maximum temperature arise only from heat input at the surface. A more comprehensive index of pollution potential considers the mean wind speed through the mixed layer in conjunction with the mixing depth. The mean mixed-layer wind speed is calculated by simply averaging vertically the winds observed at 0000 GMT at the surface and standard pressure level up to (or immediately below) the top of the mixing layer. The ventilation coefficient (Holzworth, 1974)

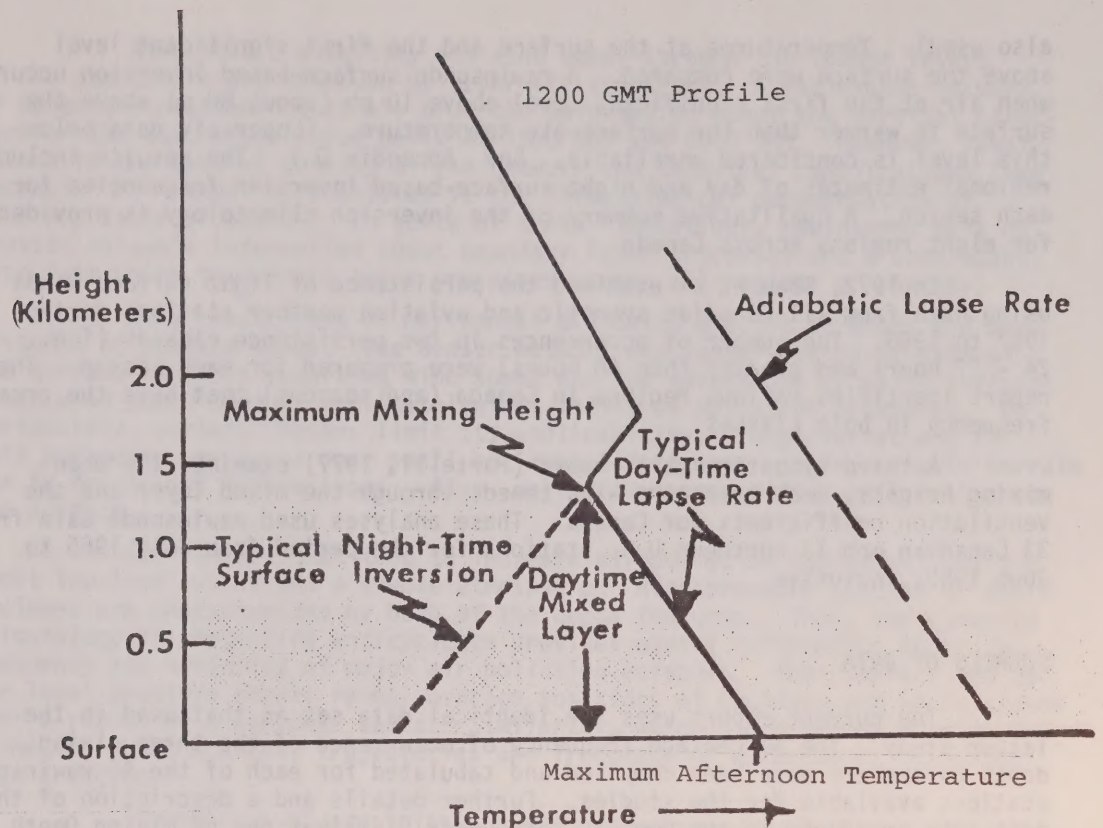

FIG. I Calculation Of Maximum Mixing Height

combines these two indices in a single value taken as the product of the maximum mixing height and the mean wind speed through the mixing layer. It represents the volumetric rate per unit distance normal to the wind direction at which air within the mixed layer is transported, and is expressed in m^2/s. The higher the ventilation coefficient, the more able the atmosphere is to disperse pollutants.

(ii) The Limitations: There are several complications that must be considered in the analysis and assessment of the pollution potential indices in this study.

First of all, the mixing depth method used to derive the indices are most applicable to mid-latitudes. Peculiarities of the Arctic such as the semi-permanent surface-based inversion during the long Polar night are not recognized in this scheme. The Arctic stations experience little or no solar radiation for six months of the year. Changes that do occur in the vertical temperature profile at these higher latitudes are due to advection or radiational cooling only (see Chapter 12: The High Arctic). A study to examine this situation is being undertaken.

Secondly, the assumption of a dry adiabatic lapse rate through the mixing layer during the occurrence of significant precipitation is questionable. These cases are not isolated in the data set used in this study.

(Holzworth, 1972, gave special treatment to precipitation and non-P cases in the U.S. mixing depth study. The tabulations showed a distinct tendency for the P mixing heights to be lower than the non-P heights in the afternoon because of the effects of dense cloudiness).

Another factor in the computations that influences the standardization of the statistics is the variation of the time zones between the east and west coasts. For example, on the Atlantic Coast 1200 GMT is 8:00 AM LST while on the Pacific Coast it is 4:00 AM LST (Yukon is 3:00 AM LST). Similarily, 0000 GMT is 8:00 PM LST and 4:00 PM LST, respectively. As much as 12 hours exist between 1200 GMT and the local daytime maximum surface heating period. During these hours, warm or cold advection can alter the temperature and wind profiles considerably. This can cause major differences between the actual and calculated mixing heights, and complicate comparisons between regions from east to west.

Finally, 'cold advection' and 'unlimited mixing' cases have been identified and isolated in the calculations.

The latter cases were flagged 'U' and arbitrarily assigned a value of 5000 metres, and are included in the statistics of mixing heights greater than 2000 m. In 'cold advection' cases, the mixing depth (and corresponding mean wind speed) cannot be computed. Allowances for C-type mixing heights and wind speeds were made in the U.S. study (Holzworth, 1972). In the current study, however, these special cases should not seriously hamper the results except in the 'cold advection' cases in the High Arctic and in certain cases in the winter at lower latitudes. In southern regions, these constitute only about 5% of the occurrences on an annual basis (Appendix E).

(iii) The Analyses: Using the data sets described in the report "Frequency Distributions of Mixing Depth Parameters In Canada" (Portelli and Wilson, 1979) percentage frequency charts and tables were prepared and analyzed for various ranges of the corresponding mixing depth parameters, and are found in Appendices A, B and C of this report. The ranges analyzed include:

1) maximum afternoon mixing heights - analyzed every 200 m, from the number of occurrences less than 200 m (i.e., extremely limited vertical mixing cases) to those in excess of 2000 m.

2) mean wind speeds through the mixing layer - analyzed every 4.0 m/s, from the number of occurrences in the calm to 4.0 m/s range (i.e., very limited horizontal mixing cases) to those in excess of 20.0 m/s.

3) maximum afternoon ventilation coefficients - analyzed every 1000 m^2/s, from the number of occurrences less than 1000 m^2/s (i.e., cases of high pollution potential) to those greater than 11,000 m^2/s.

The resulting frequency patterns (Appendix A) were evaluated and compared with previous studies in Canada and the U.S. Based on this process, it was possible to separate the various physical regions of Canada according to seasonal pollution potential characteristics. Twelve regions with differing mixing depth patterns were identified as shown in Fig. II. The regions are listed as follows:

1. Pacific (narrow coastal strip)
2. Rockies (or Western Cordillera)

3. Lee of the Rockies
4. Prairies
5. Great Lakes
6. Appalachians (or Eastern Cordillera)
7. Atlantic
8. Central Quebec-Labrador (Laurentian Plateau)
9. Mackenzie Valley
10. Hudson Bay
11. Baffin
12. High Arctic

The average percentage frequency* across each region were compiled for each of the mixing depth ranges given earlier and are given in the tables in Appendix B. The results from these tables and the summaries of significant ranges found in Appendix C are described qualitatively in the following chapters in terms of ten influencing factors listed below:

1. Topography - the location, orientation and extent of (i) major mountain ranges, (ii) deep valleys, (iii) broad plains, and (iv) large bodies of water.

2. Large scale surface characteristics such as forest cover, vegetation, exposed rock surfaces, etc. that vary the heat exchange properties and coefficient of friction.

3. Latitudinal variations that reflect the amount and duration of incoming solar radiation, and the impact on a unit surface area.

4. Mean storm tracks, stagnating anticyclones, thermal lows, mean surface flows (convergent, divergent, onshore, upslope).

5. Upper flows - such as cold vortices, mean positions of major troughs and ridges, etc.

6. Elevation - of the rawinsonde sites.

7. Natural and industrial moisture sources that may affect the data.

8. Heat sources (and sinks) - warm or cold ocean currents, ice-covered water or open leads, glacial ridges.

9. Development - industrial activity and large settled areas which introduce considerable heat, water vapour and particulates into the atmosphere and in turn alter the albedo, net radiation, etc. in the region.

10. Climatological Means - such as the mean maximum and minimum surface temperatures.

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* NOTE: Due to mesoscale influences, the mixing height statistics will vary within each region from site to site. This is particularly evident in areas of Canada where the topography varies significantly over relatively small horizontal distances, such as along the Western Cordillera. Caution is advised in using the averaged frequency data with respect to a specific site in the region. In cases where on-site upper-air data is not available it is best to use:
a) monthly mean mixing depth data, (Portelli, 1977) from a nearby rawinsonde station. (The station location should closely resemble the physical characteristics of the proposed site); or, b) the percentage frequency values interpolated between two closest rawinsonde stations.

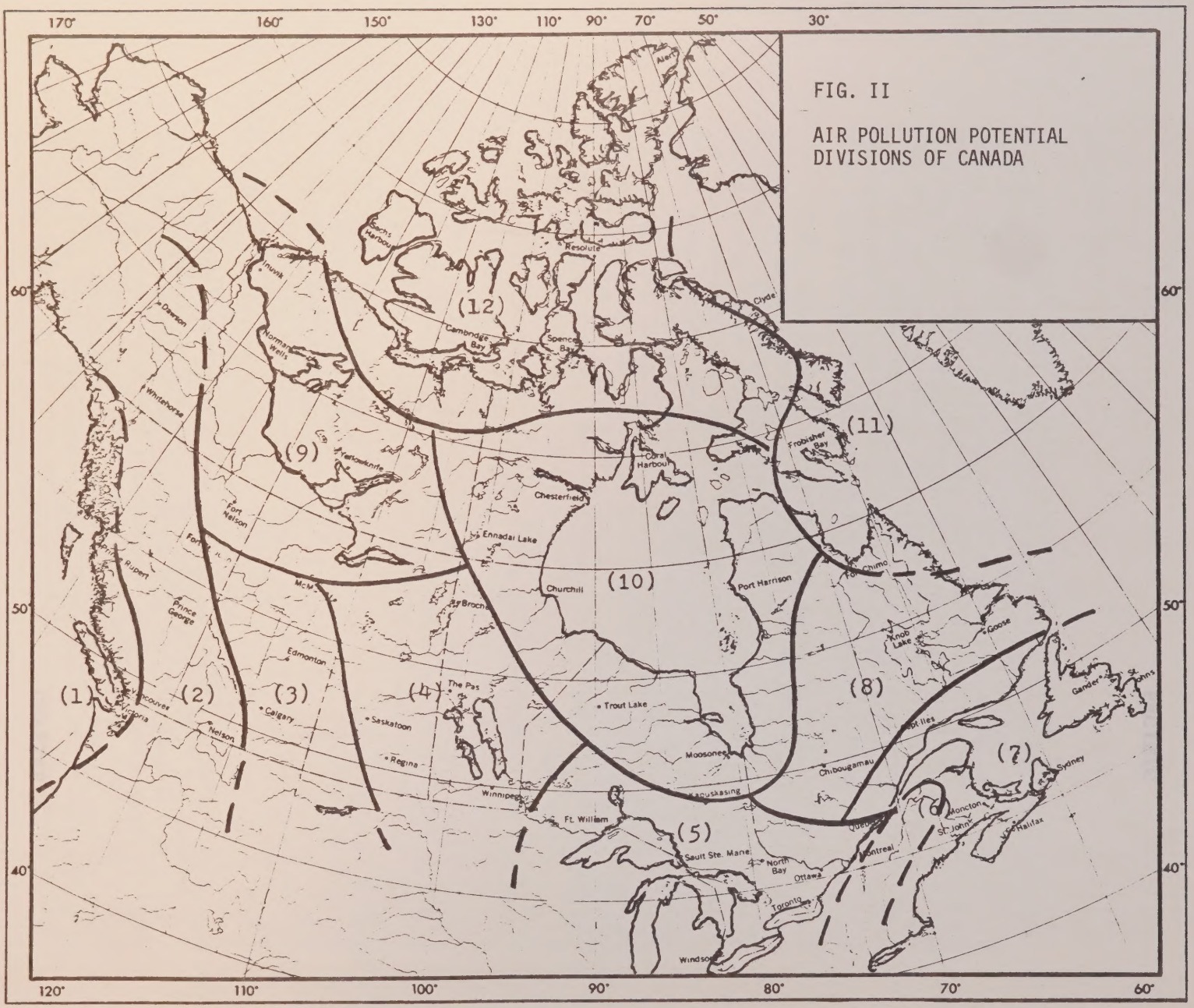
FIG. II
AIR POLLUTION POTENTIAL
DIVISIONS OF CANADA
(1)
(2)
(3)
(4)
(5)
(6)
(7)
(8)
(9)
(10)
(11)
(12)
170°
160°
150°
130°
110°
90°
70°
50°
30°
120°
110°
100°
90°
80°
70°
60°
60°
50°
40°
Alert
Resolute
Clyde
Inuvik
Norman Wells
Dawson
Whitehorse
Yellowknife
Fort Nelson
Prince Rupert
Prince George
Edmonton
Calgary
Saskatoon
Regina
Winnipeg
The Pas
Brochet
McMurray
Churchill
Ennadai Lake
Chesterfield
Baker Lake
Frobisher Bay
Port Harrison
Fort Chimo
Knob Lake
Goose
Gander
St. John's
Trout Lake
Moosonee
Chibougamau
Sault Ste. Marie
North Bay
Ottawa
Montreal
Toronto
Windsor
Moncton
St. John
Halifax
Sydney
Vancouver
Victoria
Nelson

PACIFIC

CHAPTER 1

CHAPTER 1

PACIFIC REGION

1.1 INTRODUCTION

The Pacific Region covers a narrow band along the coast of British Columbia (Fig. 1.1). Although this is the smallest region considered in this study, it is also one of the most physically diverse. The altitude varies from sea-level to between 2000 to 4000 m along the Coast Range on the eastern boundary of the region. To the west is the vast Pacific Ocean. (This is the largest body of water in the world, and covers an area greater than the combined area of all the continents - Appendix D). There are numerous islands along the coast including the Queen Charlotte Islands chain and the mountainous Vancouver Island. Innumerable long fiords and narrow river valleys wind into the interior through the Coast Range.

These topographical features cause climatic variability from one location to another throughout the region. Variations occur between the windward and leeward sides of the mountains, the inner and outer sections of the fiords and to a lesser degree with latitude. The mountains along the coast are a physical barrier that separates cold and warm airmasses. Often, super-gradient pressure and temperature patterns occur at the boundary. The total effect varies with the wind speed and angle of incidence, the barrier profile and the atmospheric thermal structure. On impact with the mountains, the form, behavior and movement of frontal zones and pressure systems are changed. Similarily, precipitation and cloud patterns are altered. On the windward slopes*, the mountain barriers increase the formation of cloud and release of heavy precipitation.

The significant differences in the climate along the Pacific Coast were summarized by Chapman (1952):

(i) Outer Coastal Division - characterized by high totals of precipitation, small proportion of snow, small annual and diurnal range of temperatures, high cloudiness and low sunshine.

(ii) Inner Coastal Division - lower precipitation, greater extremes of temperature, less cloudiness and moisture, and more sunshine especially in summer.

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* NOTE:

The windward slopes of the littoral of British Columbia have precipitation among the heaviest in the world (The Climate of Canada). The converging airmasses are forced to rise and expand into the less dense air at higher elevations, and then to cool and condense. Thus, eastward moving maritime air becomes progressively drier as it moves inland with each windward slope having more precipitation than the lee side. A good example of this contrast exists between the eastern Lower Fraser Valley on the west side of the Coast Range, and the arid conditions of the area between Kamloops and Lytton in the interior of the province.

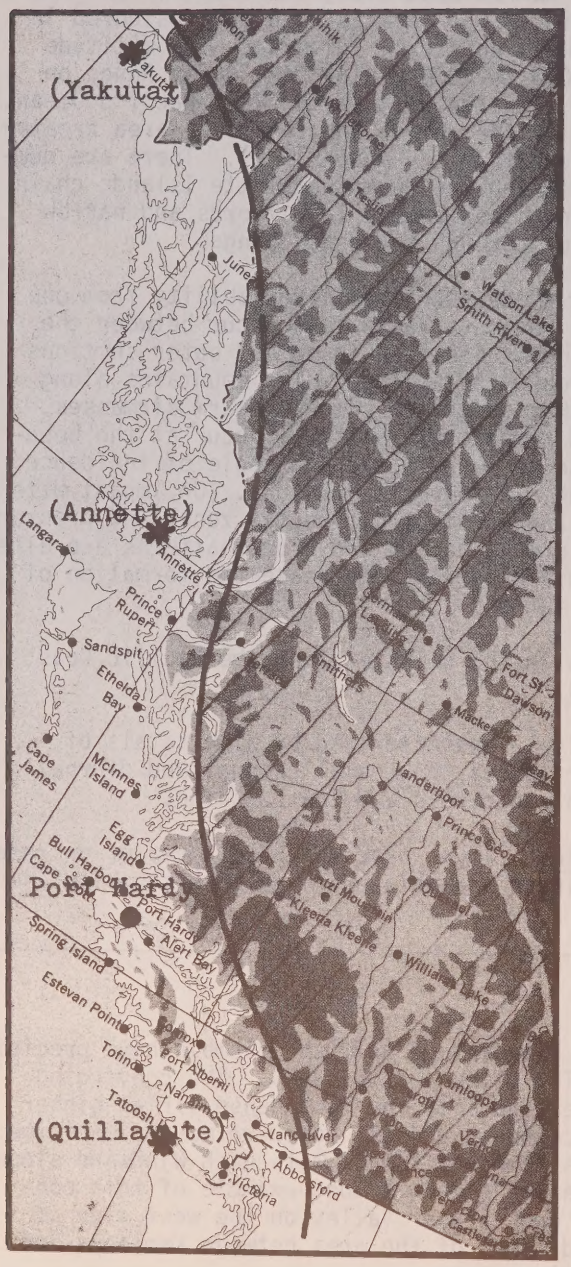

FIG. 1.1
PACIFIC REGION

● - rawinsonde stations
(* - to be included later)

(iii) Fiords - well-developed local winds and precipitation conditions with more extreme temperatures and shorter frost-free periods. This is more pronounced where long valleys extend back into the mountains ending in glaciers or acting as routeways for the westward movement of cold air from the interior during the winter.

(iv) Valleys - similar characteristics to those outlined in 3. A transition from the maritime climates of the coast to the continental conditions of the interior takes place.

In general, the topographical variabilities in the region make the lack of upper-air data along the coast a critical factor in the evaluation of the pollution potential of the Pacific region. The single rawinsonde station in the region available for this study is Port Hardy. The site fits more or less into Division (ii) above, (see Appendix D).

Other sites along the coast may vary significantly in the boundary layer from this location. For this reason, extrapolation of the Port Hardy data within the region is not advised for site specific situations. (Note: An extension of the data set to include data to 1978 is under review. It is hoped that coastal U.S. rawinsonde data from Quillayute, Annette and Yakutat (Fig. 1.1) will be available).

In spite of the above local differences, the whole area has the same broad climatic features. As a result of the prevailing westerlies, and the warm waters of the Pacific, the main climatic characteristics of the West Coast are the mild winters, the warm but not hot summers and the small range of temperatures. The region is sheltered by the mountains from winter cold waves of Arctic air. Cool sea-breezes in the summer reduce intense surface-heating found at interior locations. In addition, latitude is not the major temperature control that it is at inland sites. The dominating control of temperature by the ocean is indicated by the small variation from north to south across the region. The general precipitation regime is characterized by wet winters, (heavy cloud in autumn and winter), small portions of snow at low levels, a large number of days with precipitation, and a well-defined summer season minimum. (The less exposed districts including the east coast of Vancouver Island (for example, Port Hardy) and the Fraser Valley have very sunny skies in the summer).

1.2 MAXIMUM (AFTERNOON) MIXING HEIGHTS

1.2.1 General Charateristics

From the frequency distribution in Fig. 1.2, it can be seen that spring and summer have the best conditions for vertical diffusion during the year. In both seasons, low mixing heights occur least often and higher mixing heights occur most often (Fig. 1.3). See Appendix B, Table 1.1 for further details.

For mixing heights above 1000 m, the following seasonal frequencies are observed:

Spring	Summer	Fall	Winter
40.9	24.7	7.2	1.4

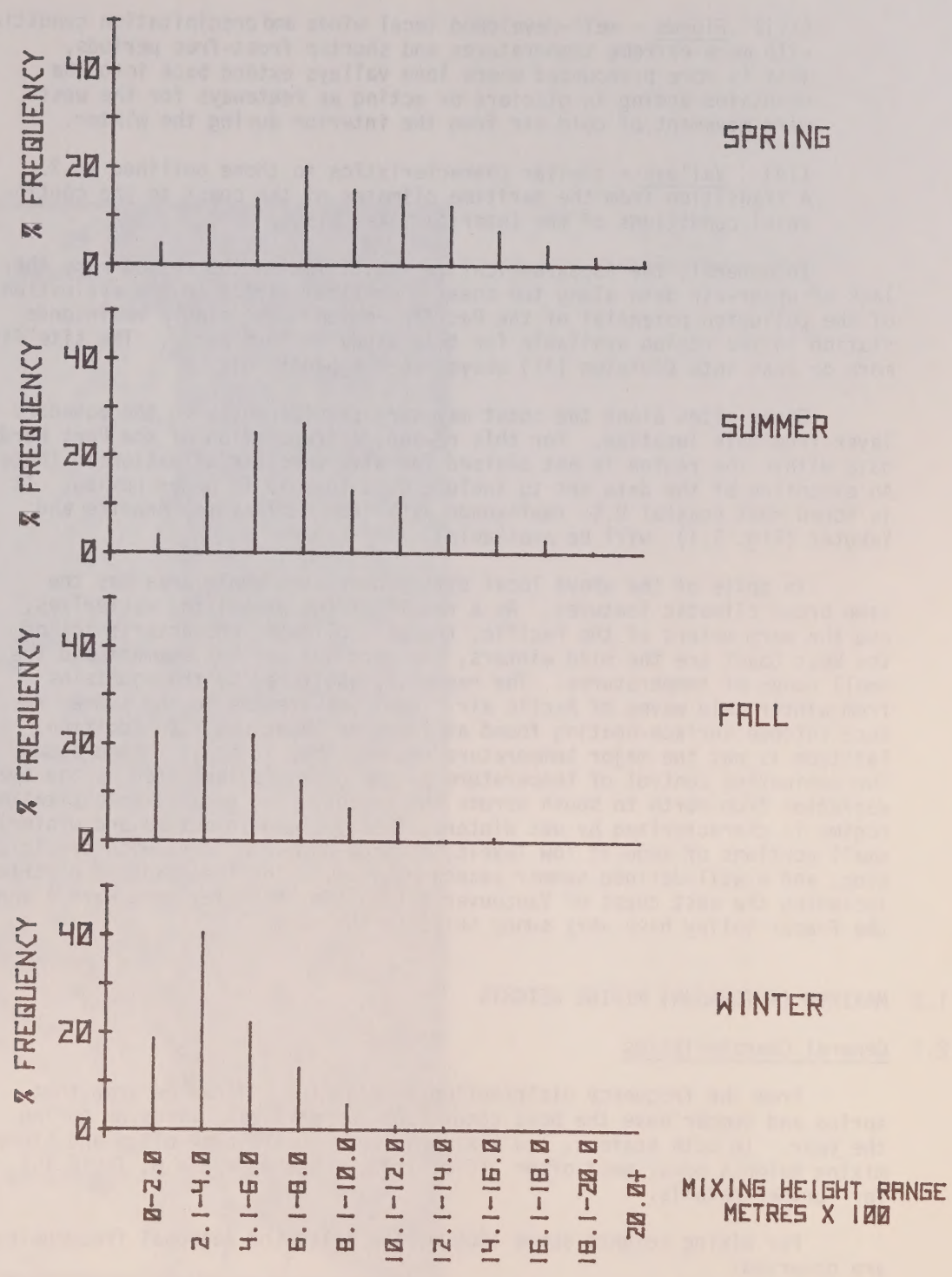

FIG. 1.2 SEASONAL FREQUENCY HISTOGRAMS OF SPECIFIED MAXIMUM MIXING HEIGHTS. REGION : PACIFIC

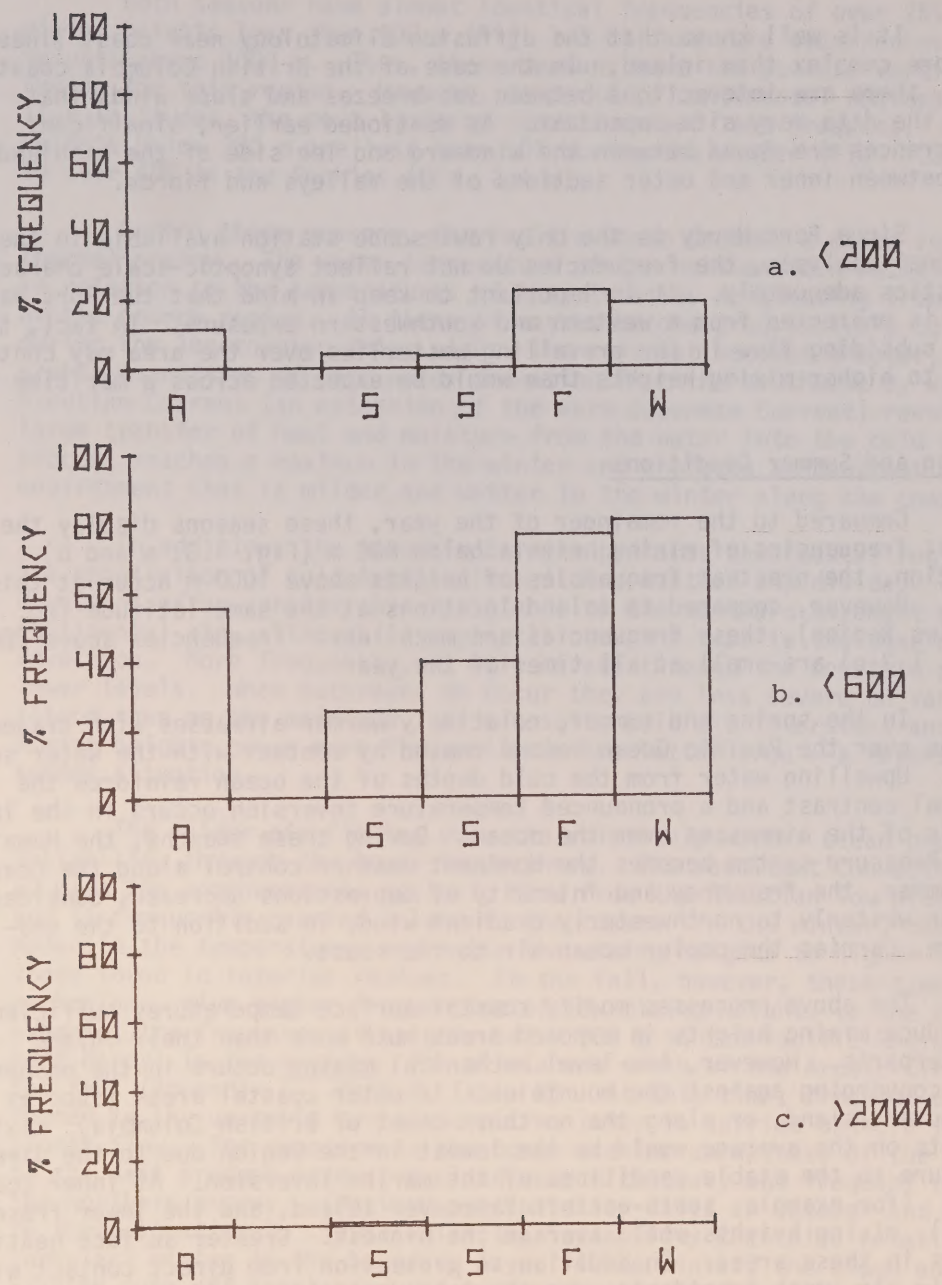

FIG. 1.3 Annual and Seasonal Frequencies of Occurrence of Maximum (Afternoon) Mixing Heights (m) for the Pacific Region

Mixing heights below 600 m occur most often in fall and winter, (Fig. 1.3 b).

It is well known that the diffusion climatology near coast lines is more complex than inland. In the case of the British Columbia coastline, there are interactions between sea-breezes and slope winds that make the data very site-dependant. As mentioned earlier, significant differences are found between the windward and lee side of the highlands, and between inner and outer sections of the valleys and fiords.

Since Port Hardy is the only rawinsonde station available in the regional analysis, the frequencies do not reflect synoptic-scale characteristics adequately. It is important to keep in mind that the Port Hardy site is protected from a western and southwestern exposure. In fact, the weak subsiding flow in the prevailing westerlies over the area may contribute to higher mixing heights than would be expected across a maritime region.

1.2.2 Spring and Summer Conditions

Compared to the remainder of the year, these seasons display the lowest frequencies of mixing heights below 600 m (Fig. 1.3, a and b). In addition, the greatest frequencies of heights above 1000 m occur at this time. However, compared to inland locations at the same latitude (eg. Rockies Region), these frequencies are much less. Frequencies above 2000 m (Fig. 1.3 c) are small at all times of the year.

In the spring and summer, relatively warmer airmasses with trajectories over the Pacific Ocean become cooled by contact with the water surface. Upwelling water from the cold depths of the ocean reinforce the thermal contrast and a pronounced temperature inversion occurs in the lower levels of the airmasses over the ocean. During these seasons, the Hawaiian High Pressure system becomes the dominant weather control along the coast. By summer, the frequency and intensity of depressions decreases considerably. A mean westerly to northwesterly gradient wind, in addition to the sea-breeze, carries the cooler ocean air to the coast.

The above processes modify coastal surface temperatures sufficiently to reduce mixing heights in exposed areas much more than their inland counterparts. However, low-level mechanical mixing occurs in the onshore flow converging against the mountains. In outer coastal areas (such as west Vancouver Island, or along the northern coast of British Columbia) mixing heights on the average would be the lowest in the region due to the direct exposure to the stable conditions of the marine inversion. At inner coastal areas (for example, south-eastern Vancouver Island, and the lower Fraser Delta) mixing heights would average the highest. Greater surface heating occurs in these areas. In addition to protection from direct contact with Pacific air, weak subsidence over the island mountains provides sunny skies during the summer. (Victoria has annual sunshine totals only slightly less than Lethbridge, the sunniest station in Canada. In contrast, Prince Rupert receives less than half this amount). The dryness at these protected sites often creates a critical shortage of local moisture in the summer months not usually associated with coastal areas at similar latitudes. This condition is compounded in the summer by the occasional penetration of warm, dry air from the Great Basin thermal low to the south.

1.2.3 Fall and Winter Conditions

Both seasons have almost identical frequencies of over 75% of the mixing heights less than 600 m (Fig. 1.3 b), and rare occurrences of mixing heights above 1000 m. Thus, these seasons have the poorest vertical diffusion for this region. However, compared to continental regions at similar latitudes, the most limiting conditions are less frequent. Mixing heights below 200 m are less than 20% during the winter (Fig. 1.3 a) compared to over 40% in the Rockies (Fig. 2.4 a).

During these seasons, the Pacific Ocean becomes a major source of thermal energy. The water temperature of the northeastern Pacific is high in relation to the temperatures of the airmasses originating from the Arctic source region. As these airmasses become progressively colder during the lengthening Polar night, the contrast becomes greater. Considerable quantities of warm water emanating from the southwest by way of the Aleutian Current (an extension of the warm Japanese Current) results in a large transfer of heat and moisture from the water into the cold air. This process reaches a maximum in the winter and produces a resultant maritime environment that is milder and wetter in the winter along the coast.

In addition, the mountain barrier protects the coastal region from the penetration of cold Arctic air building east of the divide. The Rocky Mountains offer considerable resistance to the westward movement of cold continental air, although it may spill over the tops in the case of deep advection. More frequently, it will invade through the mountain passes at lower levels. When outbreaks do occur they are less severe on Vancouver Island than on the mainland. As a result, cold air inversions and lower mixing heights occur more frequently in the latter area - a reverse of the summer situation.

The colder air flowing over the relatively warmer ocean produces instability through the lower troposphere. The resultant convection lines up with the northwesterly cyclonic flow from the Aleutian low pressure system, and is frequently carried inland to the coast. In the winter, these effects moderate the temperatures and raise the mixing heights to higher levels than those found in interior regions. In the fall, however, these same moderating mechanisms give higher frequencies of low mixing heights to the coast. For example, the frequency of heights below 600 m in the Pacific Region (i.e., Port Hardy) is the maximum for all Canada south of the Arctic Circle in the fall (Appendix C - Part 2, Table 7). At this time, frequent cloudiness formed in the unstable turbulent mixing layer is carried onshore in the cyclonic flow. The exposure to the ocean and the abruptness of the mountains to the east produce extensive cloudiness with heavy and frequent rain along the northern shores. (Maximum precipitation falls in October and November in these locations). Thus, while the instability maintains relatively good turbulent mixing in the boundary layer in the winter, the cloud and precipitation cuts off insolation and surface-heating in the fall which critically limits the mixing heights.

1.3 MEAN TRANSPORT WIND SPEED THROUGH THE MIXED LAYER

The wind speeds at locations along the coast are very site-dependant. Thus, these observations apply to the Port Hardy site specifically. However, as in the case of other coastal areas adjacent to large bodies of water, the maximum frequencies tend to occur in the higher mean wind speed ranges on an annual average. At Port Hardy, the highest annual frequencies occur in the 4.1 to 8.0 m/s range (Appendix B, Table 1.2)

There is very little seasonal variation in the frequency of calm to light mean winds through the afternoon mixing layer (Fig. 1.4 a). The lowest frequency occurs in the spring. The strongest mean mixed-layer winds, however, occur with the greatest frequency in the winter (Fig. 1.4 b).

The mean surface pressure gradient is strongest during the winter. The increased periodicity of winter storms in conjunction with the low-level instability permits greater horizontal ventilation at this time. Mean winds greater than 8.0 m/s occur more frequently in winter than during any other season.

In the summer, when the Pacific high pressure area dominates the weather pattern, light gradient winds are most common. At the same time, the maritime inversion is most persistent. Consequently, the highest frequency of mean transport wind speeds through the mixing layer less than 8.0 m/s occur at this time.

1.4 MAXIMUM AFTERNOON VENTILATION COEFFICIENTS

Annually, over half of the occurrences are in categories less than 3000 m^2/s (Fig. 1.5 a). In the summer, almost half of the cases fall in the same critical range and over 80% of the cases fall below 6000 m^2/s (Fig. 1.5 b).

The most critical period for limited horizontal and vertical dispersion along the coast occurs in the fall and winter months. At these times, almost 70% of the cases have ventilation coefficients less than 3000 m^2/s. Compared with neighbouring continental regions, however, the winter frequencies are a relative minimum. This is the result of the stronger mixed layer winds and less frequent low mixing heights.

Spring has the lowest frequency of conditions below 3000 m^2/s and the highest frequency above 11,000 m^2/s (Fig. 1.5 a and c, respectively). This is the result of the infrequent low mixing heights (annual minimum) combined with the lowest frequency of light mixed-layer wind speeds.

1.5 CONCLUSIONS

More than in other regions of Canada, the regional mixing depth frequency statistics are highly dependent on mesoscale baroclinicity and vorticity effects. Topographical controls of these effects are very marked at the numerous exposed or sheltered sites throughout the physically diverse region.

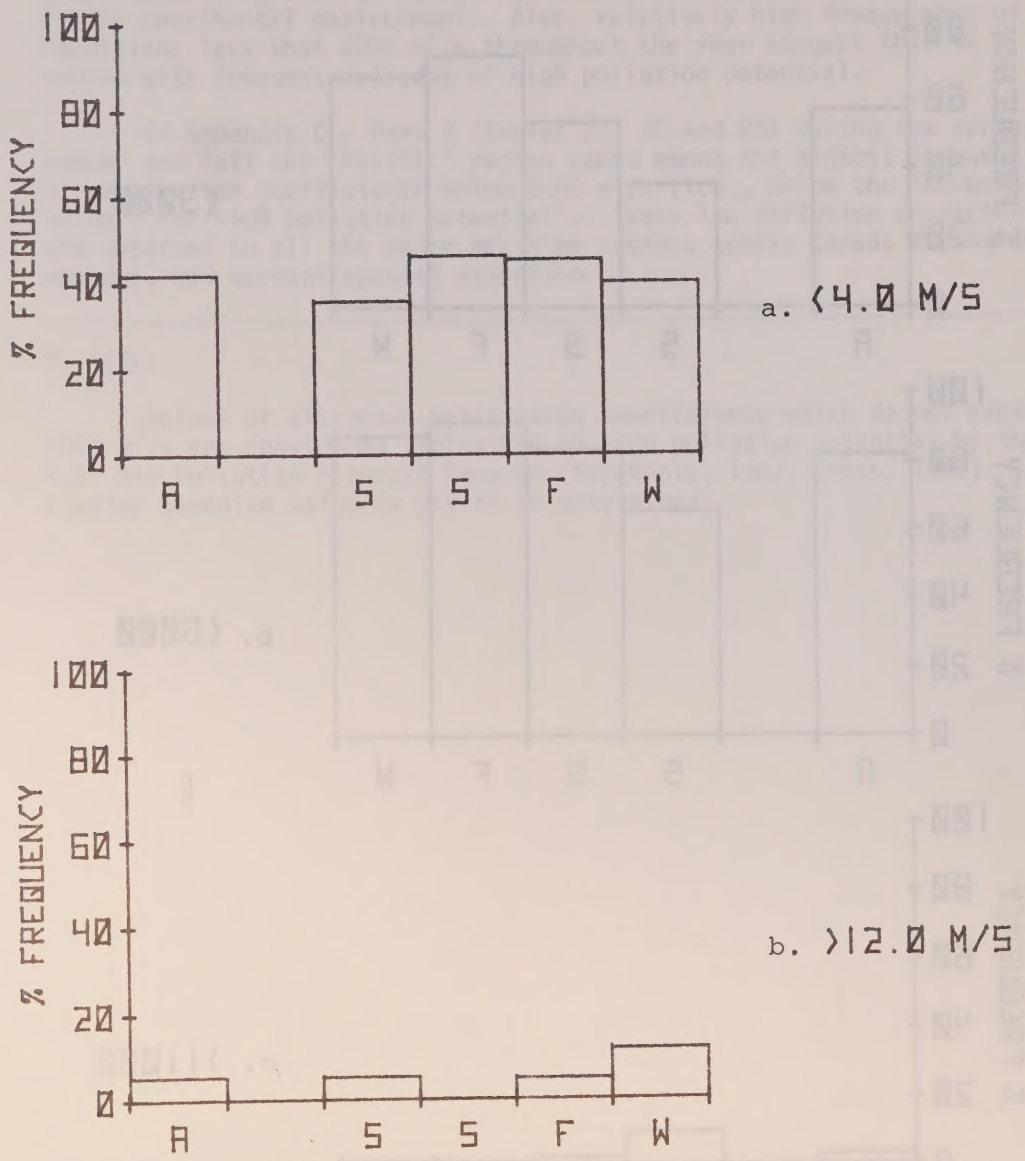

FIG. 1.4 Annual and Seasonal Frequencies of Occurrence of Mean Wind Speeds Through the Mixing Layer (m/s) for the Pacific Region

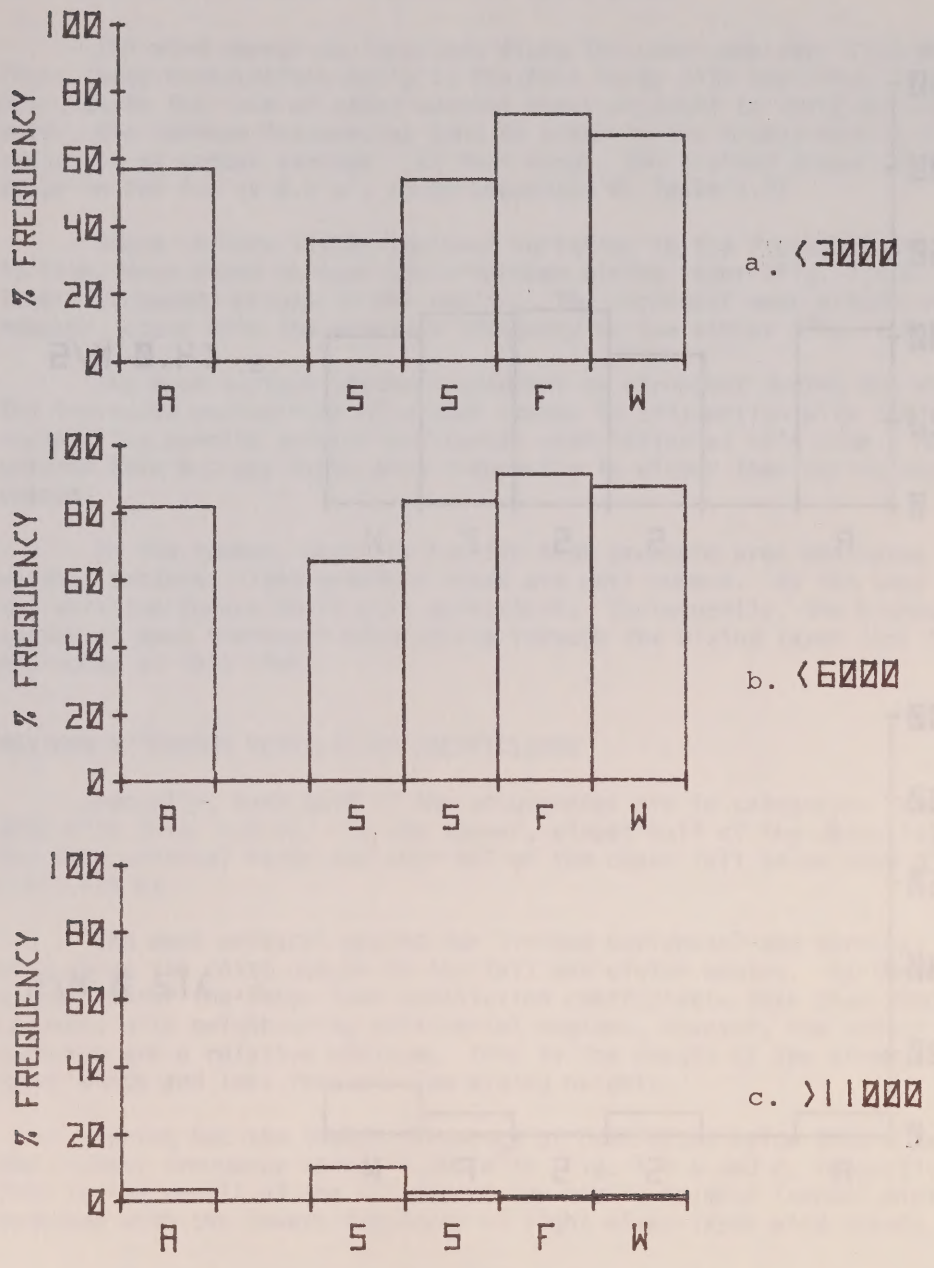

FIG. 1.5 Annual and Seasonal Frequencies of Occurrence of Afternoon Ventilation Coefficients (m^2/s) for the Pacific Region

As described earlier, the data relates specifically to the relatively sheltered Port Hardy site. Seasonal variations in the data, however, reflect the coastal environment. For example, little differences occur in the frequencies from season to season compared to an interior continental environment. Also, relatively high frequencies of conditions less than 6000 m^2/s throughout the year suggest this is a region with frequent episodes of high pollution potential.

In Appendix C - Part 2 (Tables 21, 22 and 23) during the spring, summer and fall the 'Pacific' region ranks among the highest frequencies of ventilation coefficients below 6000 m^2/s (i.e., below the 'threshold value'* for high pollution potential). These low diffusion characteristics are observed in all the major maritime regions across Canada during these seasons, and warrant special attention.

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* NOTE:

Values of afternoon ventilation coefficients which do not exceed 6000 m^2/s are considered indicative of high pollution potential by the U.S. Air Pollution Forecast Program (Stackpole, 1967; Gross, 1970). A similar Canadian value is yet to be determined.

WESTERN CORDILLERA

CHAPTER 2

CHAPTER 2

ROCKIES REGION

(WESTERN CORDILLERA)

2.1 INTRODUCTION

Like the Pacific Region, the 'Rockies' Region which is comprised of a large segment of the Canadian Western Cordillera (Fig. 2.1), is one of considerable physiographical diversity. Some of the main features that influence boundary layer conditions on a synoptic-scale include the following:

1. The Ranges: The extremely rugged terrain consists of ranges with elevations that vary between 2000 to 4000 m. The main systems include - the Rocky Mountains, the Selkirk Mountains and the Coast Mountains in the south; and, the Mackenzie Mountains to the Alaska Range (St. Elias Mountains) across the Yukon. They are oriented along a northwest-southeast direction essentially parallel to the Pacific coastline. These ranges provide a strong barrier to the maritime influence from the Pacific to the west, and to the cold Arctic air from the Great Plains to the east.

2. The Valleys: Deep, sheltered interior valleys and plateaus with embedded lakes and river systems cut between the ranges. The most notable align approximately north-south, parallel to the major mountain ranges, and allow cold air masses from northern sections of the region to drift southward. These valleys include:

i) the Columbia River Valley, Okanogan Valley, Fraser River Valley and the Rocky Mountain Trench in the south,

ii) the Nechako Plateau, Skeena River Valley, and the upper portions of the Fraser and North Thompson Valleys in central and northern British Columbia.

iii) the Interior Plateau, and the numerous river valleys in the Yukon.

(Note: A number of main valleys that contain moderate to heavy industry lie east/west, i.e. South Thompson, Nechako/Francois Lake, Peace and Pine.)

3. The Passes: Mountain passes open into many of these protected valleys and plateaus. The Coast Range for example, has numerous fiords and narrow river valleys that provide passage to warm, moist air from the Pacific coast. Through central British Columbia, just west of the Peace River District, the Peace Reach cuts a relatively wide east-west passage through the Rocky Mountain Chain. Other major passes through the latter mountain chain include -

i) the Crowsnest Pass: - which opens directly into the plains (west of Pincher Creek and Lethbridge in Alberta). This provides a channel for air from the central valleys and the Pacific to flow into Alberta. Similarily, cold air from the plains may

FIG. 2.1
ROCKIES REGION

(WESTERN CORDILLERA)

● - rawinsonde station sites
(* - to be included later)

penetrate into the B.C. interior.

ii) the Kicking Horse Pass: - and Bow Pass north of Lake Louise.

iii) the Rogers Pass: - through the Selkirk Mountains, from the Rocky Mountain Trench.

iv) the Yellowhead Pass: - just west of Jasper.

4. The Glaciers: Snow-capped peaks and permanent glaciers have the greatest impact on the mesoscale. In addition to the generally colder air at higher elevations, these features contribute to stable lapse rates near the surface in the surrounding areas. For example, the area surrounding Lake Louise has low mean surface temperatures in the summer due to the influence of the neighbouring glacier. These numerous colder areas at higher altitudes act as regional sources for cold air drainage onto the heated plateaus and valleys below.

5. The Forests: The dense forest cover on many of the valleys and lower slopes is an important factor that determines the reflective and thermal properties of the region. Furthermore, additional moisture is available to the region through evapotranspiration; the tree cover dampens mean wind speeds near the surface; and forest fires during the dry seasons contribute to the overall surface-heating characteristics.

6. The Pacific Ocean: The proximity and orientation with respect to the Pacific Ocean influences the pollution potential characteristics of this mountainous region. As Pacific airmasses move from the west to east over the region, they are forced to ascend on the windward side and descend on the leeside of the successive northwest-southeast aligned ranges. Not only does this result in markedly higher totals of precipitation on the windward side than to the lee, but also in a decrease of precipitation from west to east as the air becomes progressively drier (see Fig. 2.2).

7. The Latitude: The region extends between the Canadian - United States border in the south, to the southern Yukon in the north. Unlike the Pacific region, however, large variations in surface temperature do occur with latitude, reflecting the continental character of the region and the drastically reduced influence of the Pacific Ocean on this protected interior climate.

The above elements act in various ways to define the regional characteristics of the lower atmosphere during the different seasons. However, the extreme variability of the terrain features over relatively small horizontal distances results in numerous local anomalies and makes data throughout the region very site-dependent. For this reason, extrapolation of the upper-air data from rawinsonde stations even close to a particular site in the region must be done cautiously taking into account local effects. Ideally, it would be desireable to have local site-specific data obtained by routine mini-sonde flights. This is normally an expensive procedure with a limited period of operation. Boundary layer climatology from neighbouring rawinsonde stations that have longer periods of data to support statistical observations may provide complimentary information to a local study influenced by the same regional climate controls.

Three rawinsonde stations available in this study were selected to represent conditions along interior parts of the Western Cordillera.

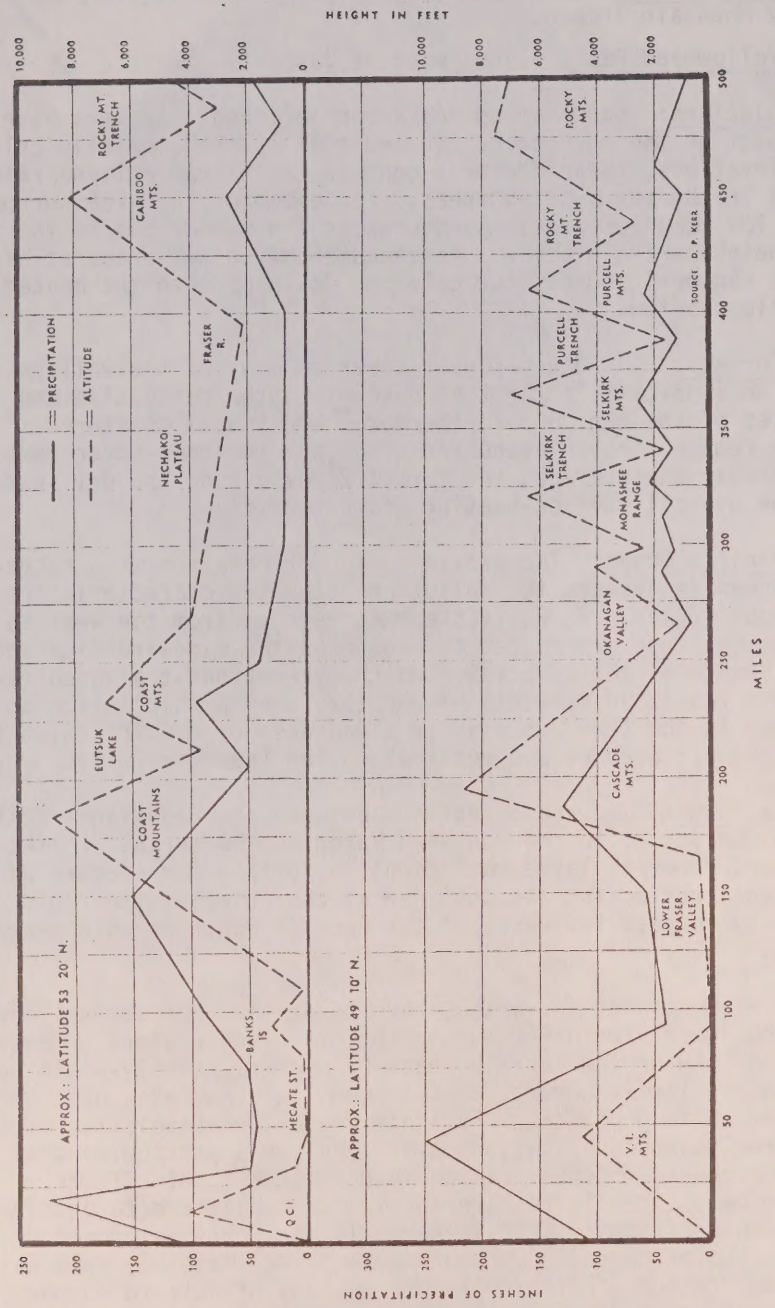


FIG. 2.2 Relationship of Altitude and Precipitation in British Columbia (Chapman, 1952)

These are Whitehorse, Prince George and Spokane. (See Appendix D for further details). Vernon, B.C. data was not available in the dataset used in this study, (1965-1969). In the expanded dataset presently under review, this information will be available.

All sites of the above stations considered in the regional analysis are essentially valley locations (i.e., with respect to the surrounding mountains) although the plateau elevations on which they are situated are considerably higher than sea-level (about 600 to 700 m ASL). The greater settled and industrial areas of the region, however, are found along the valley floors below the radiosonde release sites. Moreover, the first point taken from the radiosonde trace is approximately 100 m above the surface (see Appendix D). As a result, mean mixing depth statistics derived from the rawinsonde data would be conservative estimates of high pollution potential for sites along the river valleys, due to the drainage and ponding of colder air at these locations.

Recognizing these data limitations, and the mesoscale topographical controls, the following sections describe the mixing depth statistics from these rawinsonde stations in terms of factors that influence the regional climate on a seasonal basis.

2.2 MAXIMUM AFTERNOON MIXING HEIGHTS

2.2.1 General Characteristics

Throughout the annual and seasonal frequency charts found in Appendix A.I, the geography of the region is visible in the patterns. For example, in the lowest mixing height category (i.e., mixing heights less than 200 m), a minimum frequency 'ridge' extends along a northwest-southeast line through the region. (A reciprocal higher frequency 'trough' runs parallel to this to the lee of the mountains). For mixing heights greater than 2000 m, the frequency pattern along the mountains is a pronounced maximum with the highest frequencies extending from the southeast.

Compared to the Pacific region, the mixing height frequency values in the mountain region show pronounced seasonal variability. For example, Fig. 2.3 indicates that very small frequencies of conditions below 600 m in the summer increase to over 80% in the winter. At the same time, mixing heights above 2000 m occur in over 50% of the cases in the summer, in contrast to near zero frequencies in the fall and winter.

The above seasonal contrasts across the region are a direct result of the influence of the mountain ranges. In different seasons, the mountains:

1. shield interior plateaus and valleys from, (i) modification by the ocean to the west, and (ii) invasions of cold Arctic air from the northeast.
2. trap, (i) cold, dense air (caused by drainage or advection) in the lowest levels often resulting in lower temperatures in the valley than along the higher slopes, or (ii) surface heat concentrated along the southern plateaus and exposed slopes.

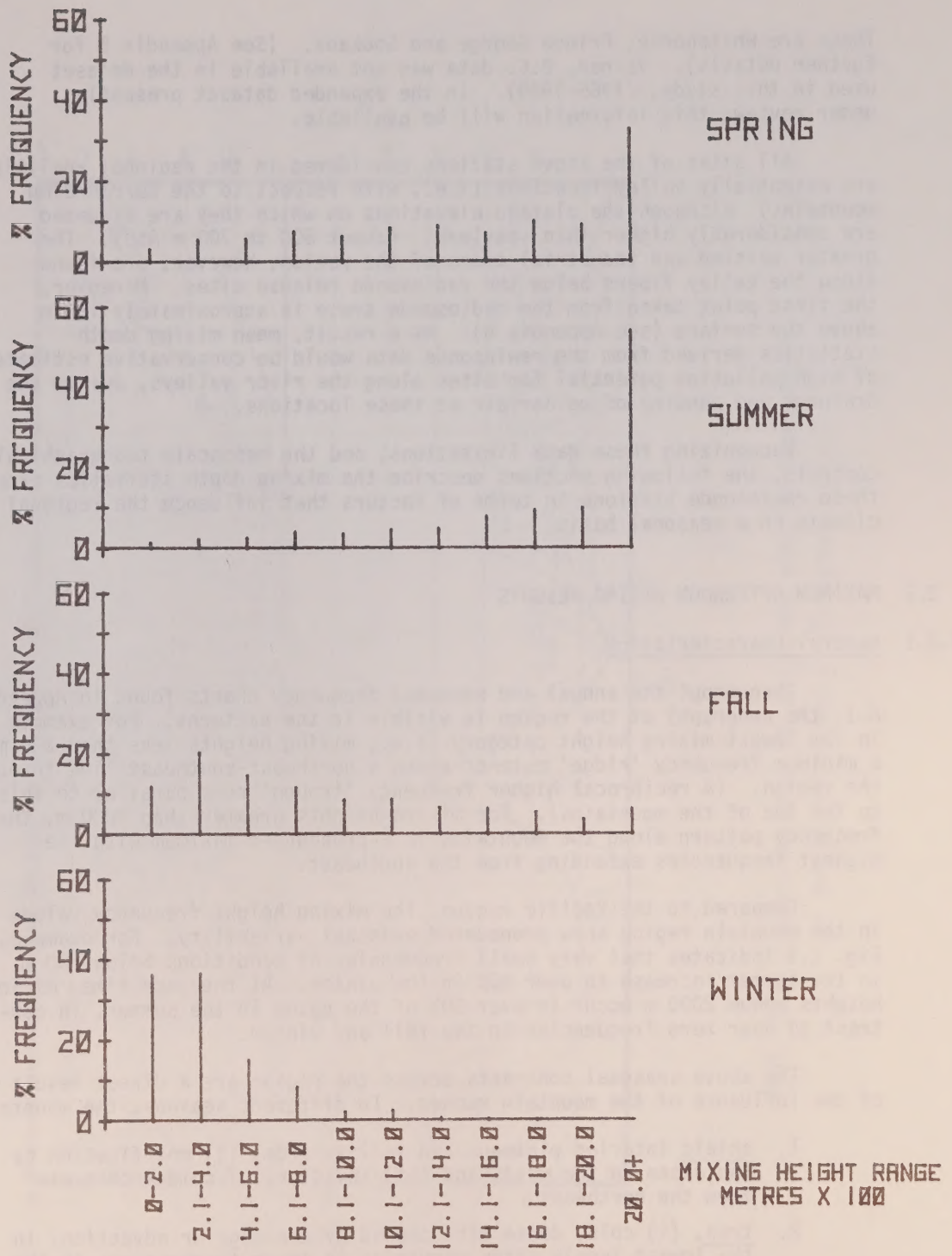


FIG. 2.3 SEASONAL FREQUENCY HISTOGRAMS OF SPECIFIED MAXIMUM MIXING HEIGHTS. REGION : ROCKIES

3. channel, (i) very cold, dry air from the Yukon or Alaska to the north, or (ii) very warm, dry air from the Great Basin thermal low pressure area to the south.

4. alter the vertical wind profile through, (i) mechanical interaction that causes pronounced turbulent eddies and vortices, and, (ii) super-gradient pressure patterns that produce strong local vertical wind shear.

5. alter the horizontal temperature and moisture gradient resulting in, (i) rainshadow areas - i.e., arid conditions to the east of the ranges in the prevailing westerly flow. For example, to the lee of the Coast Range, there are desert-like conditions in the area between Kamloops and Lytton, B.C., and (ii) heavy precipitation areas - such as Revelstoke where locally heavy snowfall necessitates the traditional tin roofs.

The following seasonal details elaborate on some of the above modifications caused by the surrounding terrain.

2.2.2 Spring and Summer Conditions

The spring and summer patterns differ significantly from those of fall and winter. High frequencies of mixing heights above 1800 m occur in spring and summer compared to low frequencies in the same ranges in fall and winter (less than 10% and zero, respectively). Low frequencies of heights below 600 m occur in spring and summer while high frequencies occur in these ranges in the fall and winter (Fig. 2.4 b). In the summer, the frequencies of mixing heights below 600 m are an annual minimum occurring less than 10% of the time.

As in the case of the annual pattern, low mixing heights occur less often over the region than along the coast or to the lee of the mountains, and high mixing heights occur most often across the south. Since the region is located in the rainshadow of the Coast Mountains, it is well-protected from the modifying influence of the maritime air to the west. During the spring and summer, the Pacific Ocean cools areas along the coast. Inland, however, the Rockies region enjoys the benefit of warm, Pacific air without the cooling and dampening effect of direct contact with the ocean. Intense surface-heating resulting from peak seasonal insolation and lee subsidence warming develops a quasistationary thermal low pressure area across southern British Columbia. The mean surface temperatures and extreme maximums are highest in the south where very hot air is channelled from the Great Basin in the states. Frequently in the summer, maximum surface temperatures in southern B.C. (near Vernon) are dry-adiabatic extensions of morning conditions from as high as the 650 mb level. Superadiabatic afternoon lapse rates and 'unlimited' mixing are common under these conditions. In summary, (1) protection from the cooling maritime influence by the mountains, (2) the drying and warming effect on the Polar Maritime air descending on the lee side of the coast range, and (3) the Tropical Continental air coming up from the south contribute to the high frequencies of mixing heights above 600 m observed across the south, (Appendix A.1 - Spring and Summer).

Munn et al (1960) noted that although ground-based radiation inversions dissipate almost every morning, the pollution potential of a deep valley may become very high during periods when there is an inadequate exchange rate with the clearer air aloft. Such cases of limited exchange occur when, (i) an intense subsidence inversion occurs in a strong high pressure ridge, (ii) weak upper winds are unable to breakdown low-level inversions and cause mixing with the warmer layers aloft, and (iii) daytime heating is insufficient to produce convective mixing through a layer deep enough to break through the inversion.

In the spring, the prevailing upper winds are westerly to southwesterly over the regions providing a good subsidence flow over the coastal and interior ranges and by summer, the upper ridge builds directly over the region. This mean upper pattern is reinforced by a weak surface pressure gradient circulation. These factors are compounded by intense radiational cooling at night under mainly clear skies, so that cold air is pooled in the valleys and low-level inversions result. When this cold air is deep enough and the winds are light, periodic stagnating conditions will persist through the day along the deeper valleys. (These valley inversions also explain why afternoon convective showers and thunderstorms are more common along the higher ridges and exposed slopes, but seldom present in the deeper valleys). In the summer, however, incursions of hot air from the Great Basin will reach most sections of the Fraser Valley, along the Rocky Mountain Trench and as far north as Quesnel and Prince George, reducing extended periods of stagnation in these areas.

Reductions in incoming solar radiation will also limit mixing in the lower valleys. In this region, daytime surface-heating may be reduced by, (a) the advection of cloud with synoptic systems and frontal activity from the Pacific (infrequent in the summer), (b) the formation of dense radiation fog that persists during the day, (usually in high precipitation areas or following intense convective storms), (c) thick smoke from widespread forest fires, and (d) major convective development. In the cases of frontal and convective activity, relatively good mixing due to mechanical turbulence and convective overturning would be maintained in spite of the reduced insolation.

2.2.3 Fall and Winter Conditions

During these seasons, the frequencies of mixing heights below 600 m reach a maximum for the rawinsonde stations in the region. In the fall, these conditions occur on the average in almost 50% of the cases and in winter, they occur over 85% of the time (Fig. 2.4b). At the same time, the frequencies of mixing heights above 2000 m drop off drastically in both seasons (Fig. 2.4c).

In the fall, the relative minimum frequency axis is still evident on the lower level mixing height charts in Appendix A.I. Nevertheless, over 55% of the cases remain concentrated in the lowest 800 m above the surface in this region. In the winter, although there is a greater frequency of low mixing heights to the lee of the mountains, most cases have mixing heights below 400 m in the mountains.

From fall to winter, cold Arctic outbreaks that manage to penetrate across the divide from the northeast and east, increase in frequency and

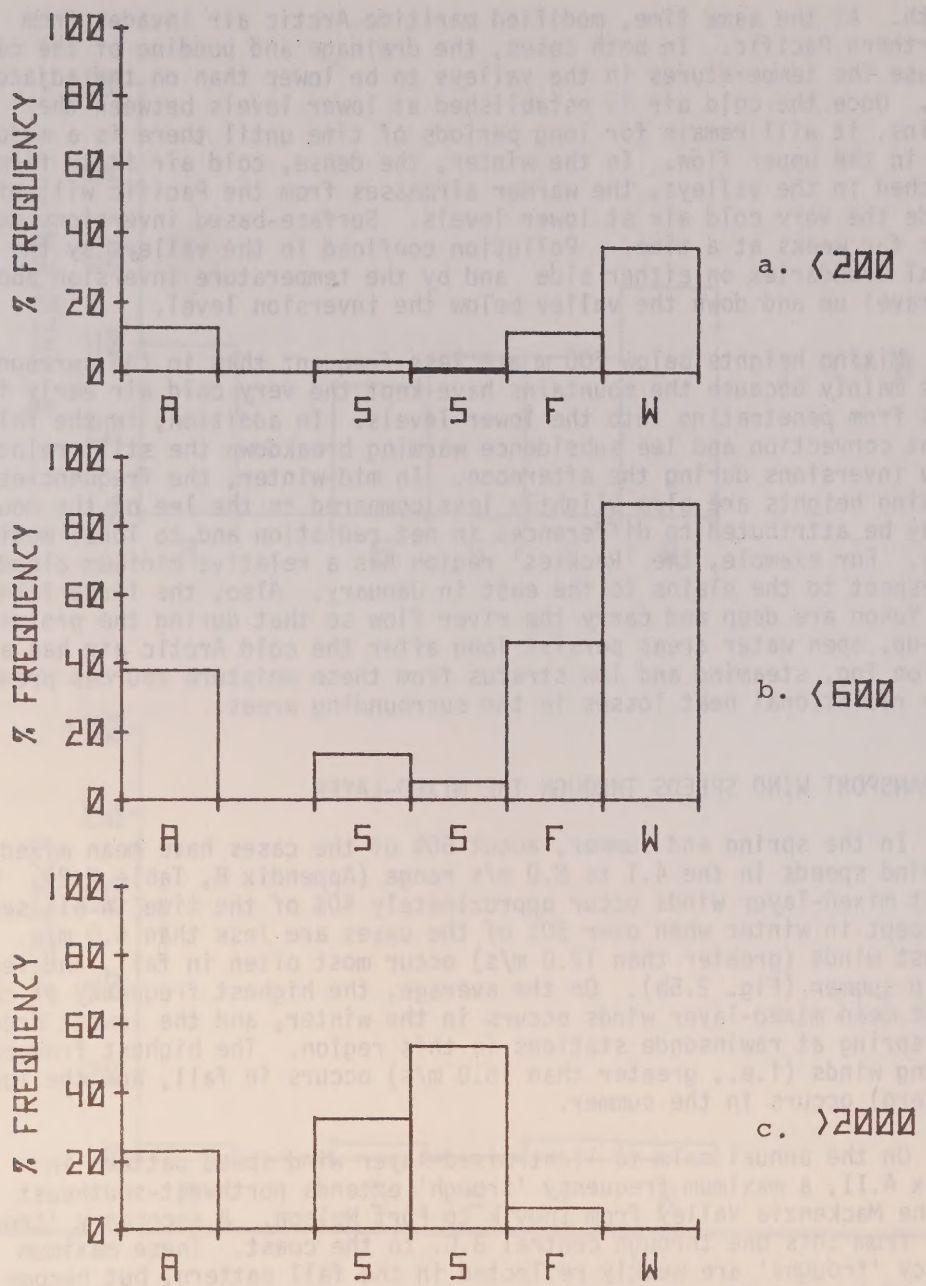


FIG. 2.4 Annual and Seasonal Frequencies of Occurrence of Maximum (Afternoon) Mixing Heights (m) for the Rockies Region

strength. At the same time, modified maritime Arctic air invades from the northern Pacific. In both cases, the drainage and ponding of the cold air cause the temperatures in the valleys to be lower than on the adjacent slopes. Once the cold air is established at lower levels between the mountains, it will remain for long periods of time until there is a major change in the upper flow. In the winter, the dense, cold air is so firmly entrenched in the valleys, the warmer airmasses from the Pacific will often override the very cold air at lower levels. Surface-based inversions may persist for weeks at a time. Pollution confined in the valleys by the physical boundaries on either side and by the temperature inversion above will travel up and down the valley below the inversion level.

Mixing heights below 200 m are less frequent than in the surrounding regions mainly because the mountains have kept the very cold air early in the seasons from penetrating into the lower levels. In addition, in the fall frequent convection and lee subsidence warming breakdown the still relatively shallow inversions during the afternoon. In mid-winter, the frequencies of low mixing heights are also slightly less compared to the lee of the mountains. This may be attributed to differences in net radiation and to local modifications. For example, the 'Rockies' region has a relative minimum albedo with respect to the plains to the east in January. Also, the large lakes in the Yukon are deep and carry the river flow so that during the prolonged freeze-up, open water areas persist long after the cold Arctic air has arrived. Advection fog, steaming and low stratus from these moisture sources prevent intense radiational heat losses in the surrounding areas.

2.3 MEAN TRANSPORT WIND SPEEDS THROUGH THE MIXED-LAYER

In the spring and summer, about 50% of the cases have mean mixed-layer wind speeds in the 4.1 to 8.0 m/s range (Appendix B, Table 2.2). Calm to light mixed-layer winds occur approximately 40% of the time in all seasons except in winter when over 50% of the cases are less than 4.0 m/s. The strongest winds (greater than 12.0 m/s) occur most often in fall, and least often in summer (Fig. 2.5b). On the average, the highest frequency of calm to light mean mixed-layer winds occurs in the winter, and the lowest occurs in the spring at rawinsonde stations in this region. The highest frequency of strong winds (i.e., greater than 16.0 m/s) occurs in fall, and the lowest (near zero) occurs in the summer.

On the annual calm to light mixed-layer wind speed pattern in Appendix A.II, a maximum frequency 'trough' extends northwest-southeast along the Mackenzie Valley from Inuvik to Fort Nelson. A secondary 'trough' extends from this one through central B.C. to the coast. These maximum frequency 'troughs' are weakly reflected in the fall pattern, but become pronounced in the winter. These results are similar to those in the study of light surface winds in Canada (Shaw et al, 1972). In this study, British Columbia, northern Alberta and the Yukon experience the greatest frequency of persistent light surface winds.

Munn et al (1966) observed that although the valley inversions are not as intense as they might be in isolated hollows, the stable temperature stratification of cold air (pooled at lower levels) may be sufficient to prevent the downward transfer of the upper air moving with the speed of the synoptic wind. As a result, valley winds are generally light.

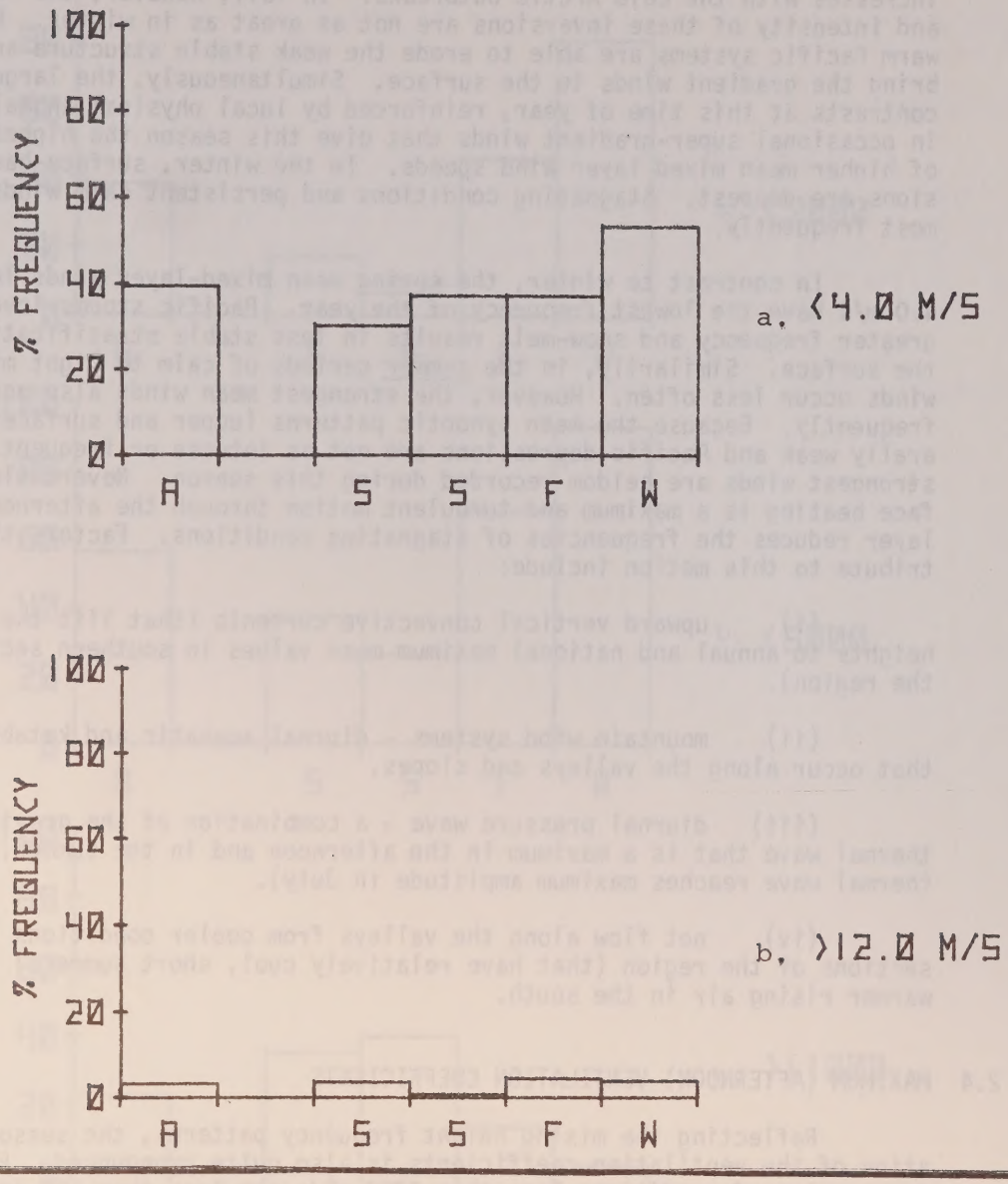


FIG. 2.5 Annual and Seasonal Frequencies of Occurrence of Mean Wind Speeds Through the Mixing Layer (m/s) for the Rockies Region

During the fall and winter, the frequency of low-level inversions increases with the cold Arctic outbreaks. In fall, however, the frequency and intensity of these inversions are not as great as in winter. Periodic warm Pacific systems are able to erode the weak stable structure and to bring the gradient winds to the surface. Simultaneously, the large thermal contrasts at this time of year, reinforced by local physical anomalies result in occasional super-gradient winds that give this season the highest frequency of higher mean mixed layer wind speeds. In the winter, surface-based inversions are deepest. Stagnating conditions and persistent calm winds occur most frequently.

In contrast to winter, the spring mean mixed-layer winds less than 4.0 m/s have the lowest frequency of the year. Pacific storms invade with greater frequency and snow-melt results in less stable stratification near the surface. Similarily, in the summer periods of calm to light mixed-layer winds occur less often. However, the strongest mean winds also occur less frequently. Because the mean synoptic patterns (upper and surface) are generally weak and Pacific depressions are not as intense or frequent, the strongest winds are seldom recorded during this season. Nevertheless, surface heating is a maximum and turbulent motion through the afternoon mixing layer reduces the frequencies of stagnating conditions. Factors that contribute to this motion include:

(i) upward vertical convective currents (that lift the mixing heights to annual and national maximum mean values in southern sections of the region).

(ii) mountain wind systems - diurnal anabatic and katabatic winds that occur along the valleys and slopes.

(iii) diurnal pressure wave - a combination of the gravity and thermal wave that is a maximum in the afternoon and in the summer. (The thermal wave reaches maximum amplitude in July).

(iv) net flow along the valleys from cooler conditions in northern sections of the region (that have relatively cool, short summers) to the warmer rising air in the south.

2.4 MAXIMUM (AFTERNOON) VENTILATION COEFFICIENTS

Reflecting the mixing height frequency patterns, the seasonal variation of the ventilation coefficients is also quite pronounced. For example, frequencies of conditions less than 3000 m^2/s are less than 10% in the summer, compared to over 80% in the winter (Fig. 2.6a). Similarily, above 11,000 m^2/s frequencies are greater than 35% in the spring and summer compared to less than 3% in the winter (Fig. 2.6 c).

In the lower coefficient ranges (i.e., less than 6000 m^2/s) spring and summer patterns in Appendix A.III show a relative minimum frequency 'ridge' extending across the region. Thus, compared to the surrounding regions, conditions for dispersion on the average are better at rawinsonde stations through the Western Cordillera during these seasons.

In contrast, fall and winter have frequent periods of limited dispersion. The greatest frequencies throughout these seasons occur below

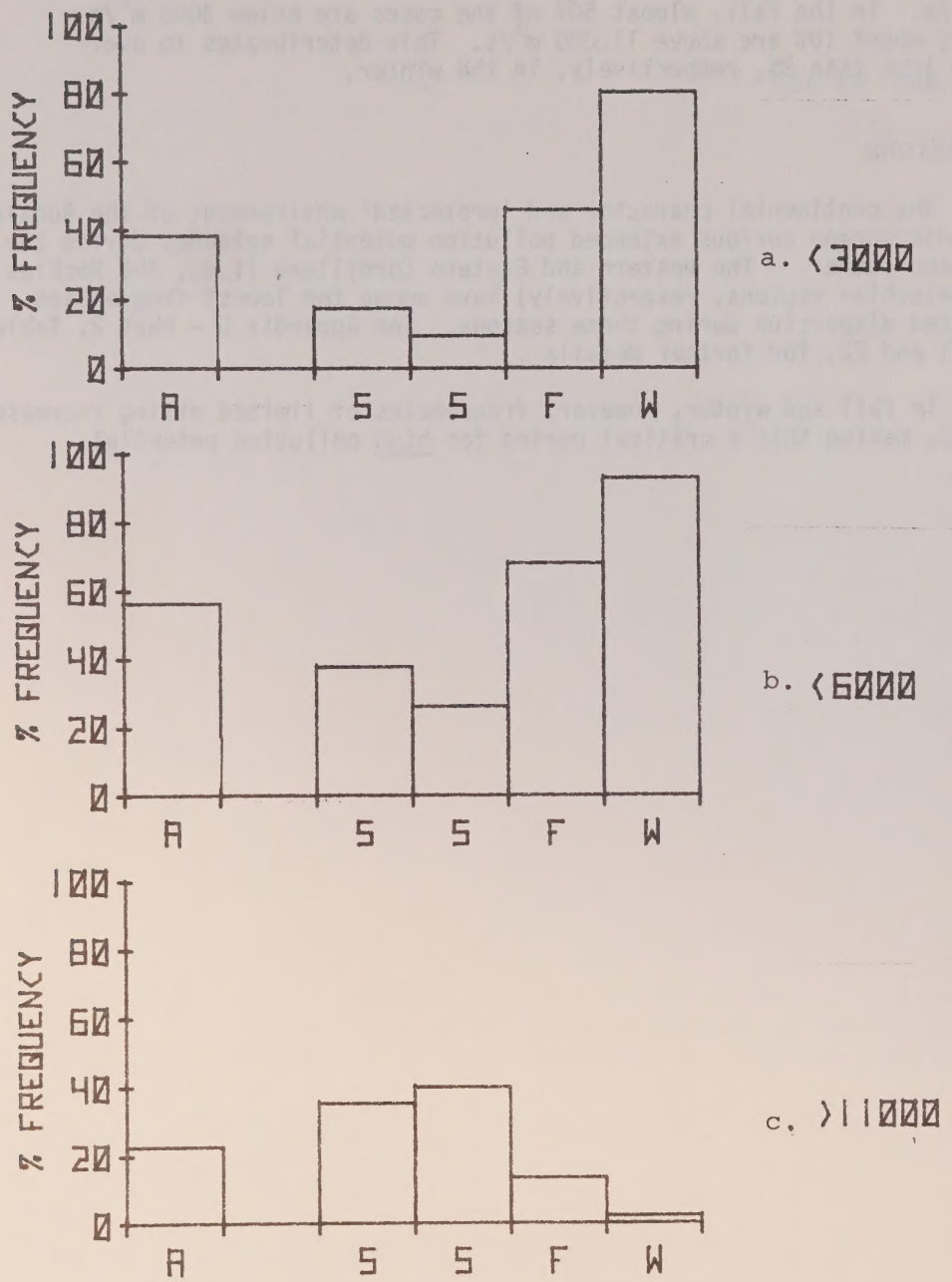


FIG. 2.6 Annual and Seasonal Frequencies of Occurrence of Afternoon Ventilation Coefficients (m^2/s) for the Rockies Region

3000 m^2/s. In the fall, almost 50% of the cases are below 3000 m^2/s and only about 10% are above 11,000 m^2/s. This deteriorates to over 80% and less than 3%, respectively, in the winter.

2.5 CONCLUSIONS

The continental character and 'protected' environment of the Rockies region discourage serious extended pollution potential episodes during the spring and summer. The Western and Eastern Cordillera (i.e., the Rockies and Appalachian regions, respectively) have among the lowest frequencies of limited dispersion during these seasons. See Appendix C - Part 2, Tables 5, 6, 21 and 22, for further details.

In fall and winter, however, frequencies of limited mixing increase markedly, making this a critical period for high pollution potential.

LEE OF THE ROCKIES

CHAPTER 3

CHAPTER 3

LEE OF THE ROCKIES REGION

(CENTRAL AND SOUTHERN ALBERTA, SOUTHWESTERN SASKATCHEWAN)

3.1 INTRODUCTION

This region is located to the lee of the Rocky Mountain Range, just east of southern and central British Columbia, and includes most of Alberta and southwestern Saskatchewan (Fig. 3.1). The section of the range to the west of the region constitutes some of the highest peaks along the chain in Canada.

The major physical characteristics that distinguish this region from others in Canada are the following:

1) The Mountains: The presence of the ranges to the west in combination with (a) the prevailing westerly flow aloft in summer, and (b) the mean northwesterly winds aloft in winter determine the seasonal variations across the region. This massive western boundary (i) acts as a barrier to moist Pacific air, and (ii) confines cold Arctic air from the north to the Prairies.

In a westerly flow aloft, the mountains cause the following classical phenomena to occur over the region:

a. Lee Cyclogensis - The vorticity in a flow perpendicular to the mountains is altered such that an anticyclonic flow is evident on the windward side, and troughing occurs on the lee side.

b. Chinooks - Rapid warming occurs mainly across the south, accompanied by strong, gusty winds. Further details are given later.

c. Mountain Waves - Turbulent vertical currents through the mid to upper troposphere occur in the wake of the higher relief and can extend for several hundred kilometres downstream.

2) The Foothills: The land immediately to the east of the range is comprised of wooded valleys that rapidly break into rolling parkland and finally drop slowly eastward to the flat, expansive plains. The mean elevation varies from 600 m to the east and northeast, increasing to between 900 and 1200 m along the foothills across the extreme southern and western sections. From the foothills, the mountain ranges to the east rise rapidly above 1800 m.

3) The Passes: The Crowsnest Pass opens directly onto the plains in southern Alberta, and provides a channel for the mild air from southern British Columbia and the Pacific to flow into the region.

In northern sections of the region, a decrease in the altitude of the Rockies north of Jasper permits rain bearing Pacific winds to penetrate into the Peace River district.

4) The Moisture Sources: The lack of large water bodies or wide rivers, and the drier Pacific air contribute to the dry, continental charac-

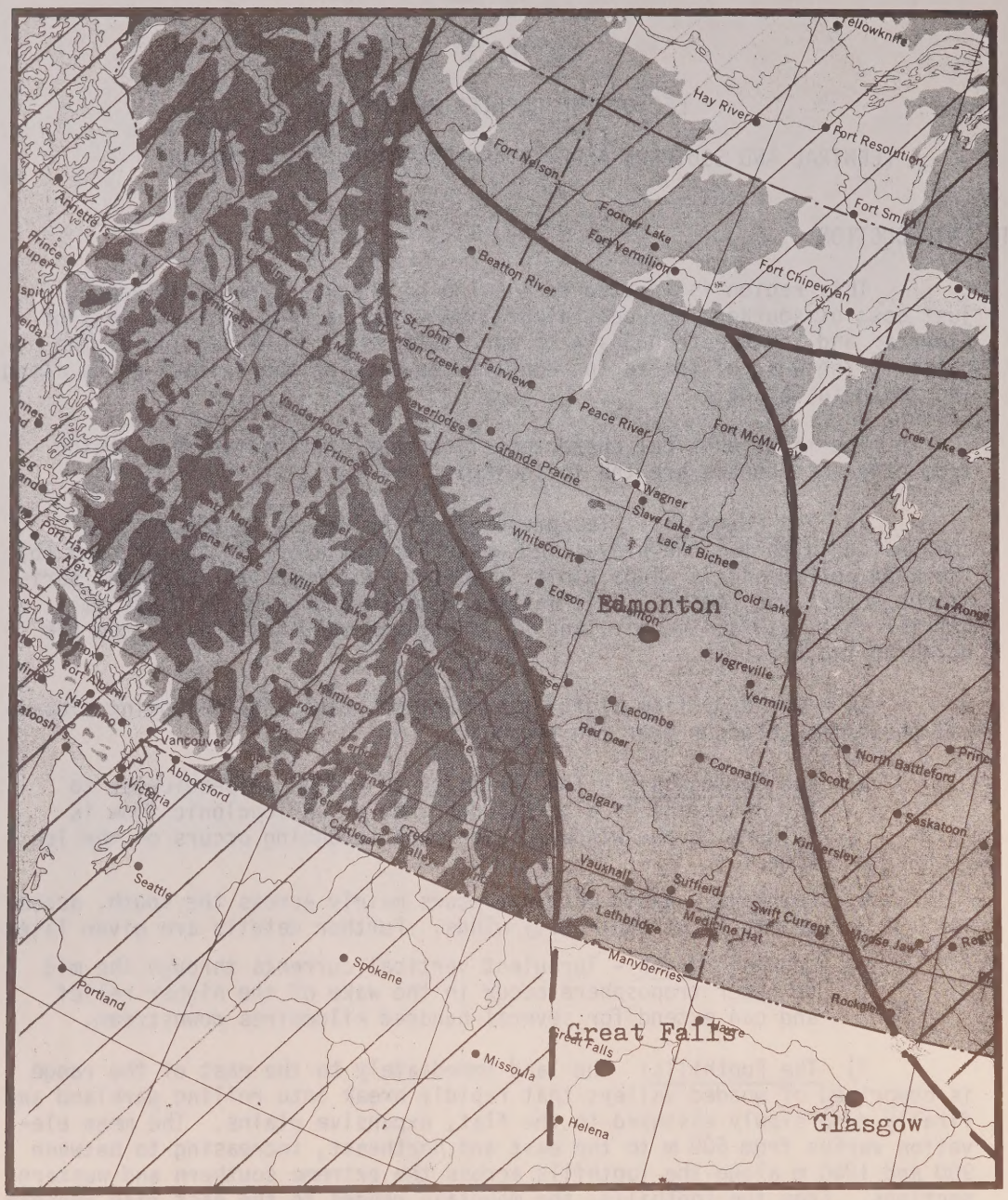


FIG. 3.1
LEE OF THE ROCKIES REGION

● - rawinsonde station sites

ter of the region. However, there are numerous small lakes and deeply eroded river valleys. The largest lake in the region in Lesser Slave Lake.

5) The Arctic Passage: The country between Alberta and the Arctic Ocean is relatively low, and provides little resistence or modification to the flow southward of colder Arctic air. There are a few higher hills within the region, however, that will alter the flow slightly. For example, the Swan Hills (3800 m) north of Edmonton often redirect the weaker cold advection in the fall to the southeast.

The rawinsonde stations selected and available in this study to represent conditions to the lee of the Rockies include Edmonton (Stony Plain), Great Falls and Glasgow (Appendix D).

3.2 MAXIMUM (AFTERNOON) MIXING HEIGHTS

3.2.1 General Characteristics

As in the case of the Rockies region, the spring and summer patterns and frequency values found in Appendix A.I and B respectively, differ greatly from the corresponding fall and winter patterns. In addition, the fall and winter patterns dominate the annual pattern. The seasonal differences however, are more pronounced to the lee of the mountains (see Fig. 3.2). High frequencies of mixing heights above 2000 m in the spring and summer contrast the relatively high frequencies of mixing heights less than 600 m in the fall and winter (Fig. 3.3 b and c, respectively). In the former case, the Lee of the Rockies experiences the highest frequencies of all regions in Canada (Appendix C - Part 2, Tables 9 - 12).

On the frequency charts of mixing heights above 2000 m a net 'ridge' of higher frequencies extends through western Montana and along the Alberta foothills and southern Rockies. Over 40% of the annual cases are concentrated at this mixing height range in this area. For low mixing heights, the annual frequency charts in Appendix A.I show a relative 'trough' of higher frequencies that extends across the region from central Alberta to southwestern Saskatchewan.

Across the region, mixing heights below 600 m occur in over 35% of the average annual cases, and above 2000 m occur in almost 30% of the cases (Fig. 3.3 b and c, respectively).

The foregoing statistics reflect the continental character of the region, and the associated seasonal variations in the temperature and pressure patterns. During all seasons of the year, the moutain barrier has an ameliorating effect on the temperature whenever the mean flow aloft has a component normal to the range. A westerly or southwesterly upper flow results in large-scale subsidence over Alberta. The resultant surface warming is proportional in intensity and horizontal extent to the strength of the gradient wind aloft. This effect is very apparent across southern Alberta to the lee of the highest peaks. Conversely, the mountains and elevated foothills act as a physical block to the cold outbreaks that frequently advance across the Prairies from the Arctic. These outbreaks occur most often from fall to spring. The resulting confined layer of cold, dense air

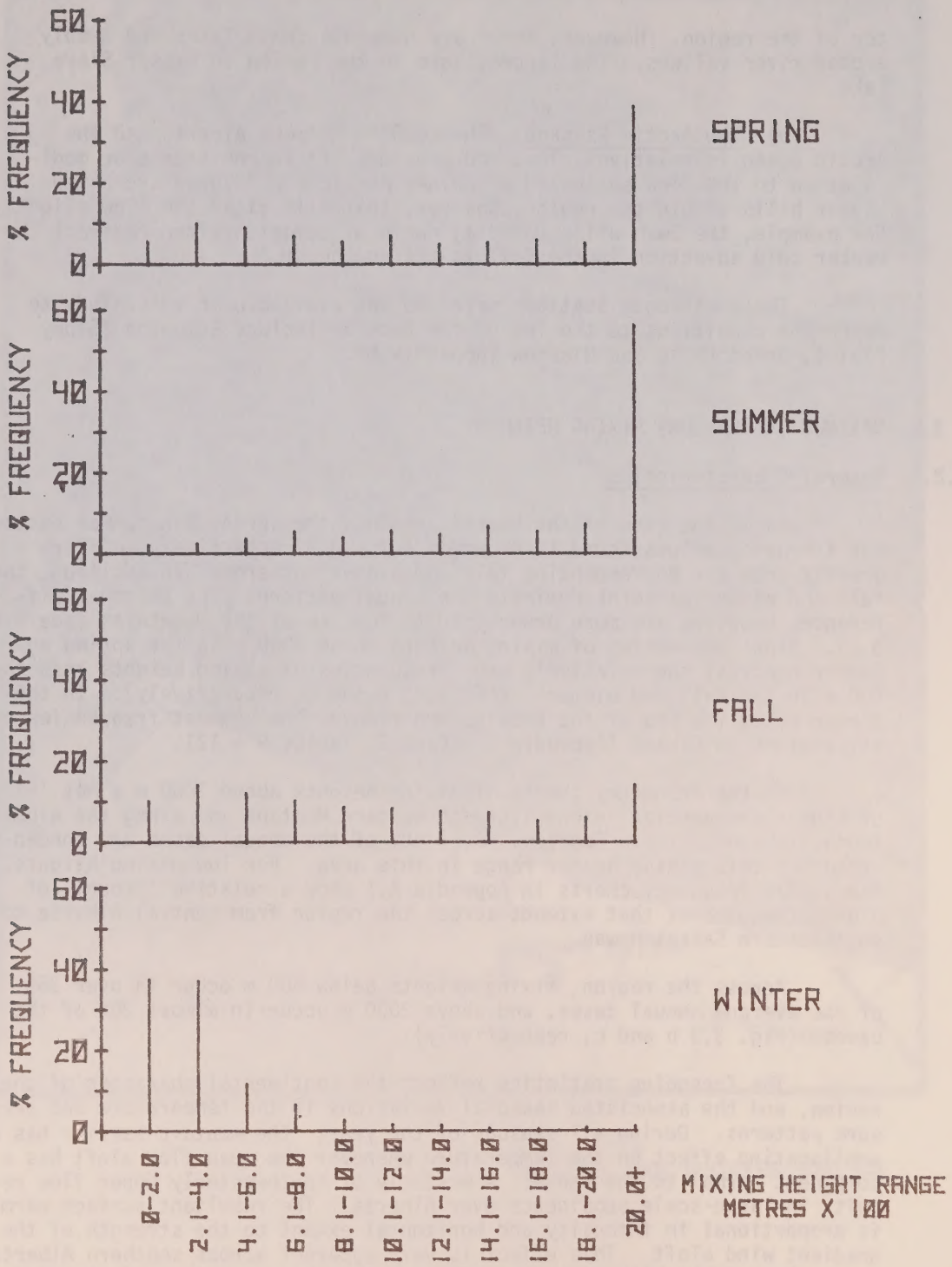


FIG. 3.2 SEASONAL FREQUENCY HISTOGRAMS OF SPECIFIED MAXIMUM MIXING HEIGHTS. REGION : LEE OF THE ROCKIES

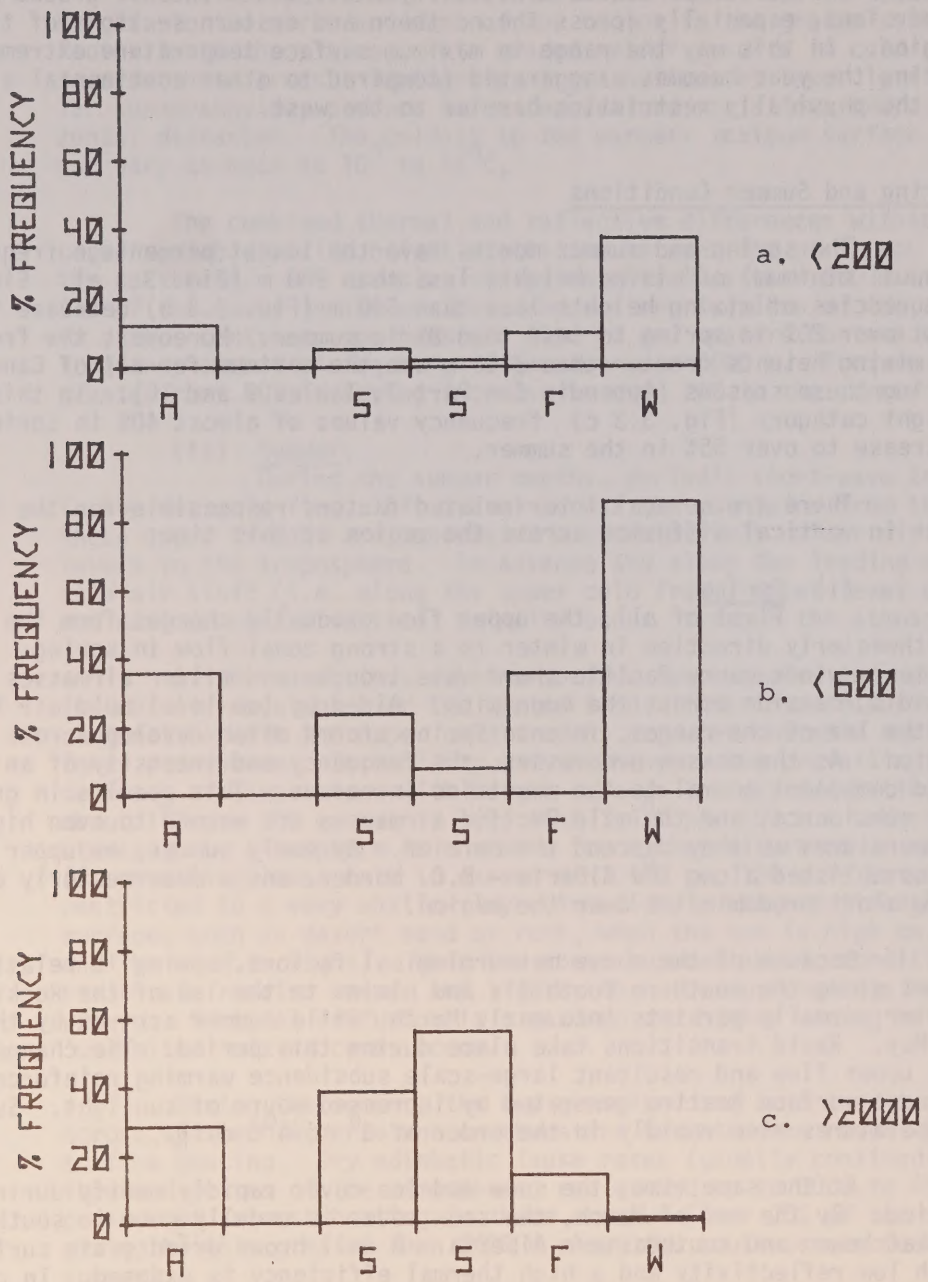


FIG. 3.3 Annual and Seasonal Frequencies of Occurrence of Maximum (Afternoon) Mixing Heights (m) for the Lee of the Rockies Region

reduces surface temperatures drastically and creates intense ground-based inversions, especially across the northern and eastern sections of the region. In this way the range in maximum surface temperature extremes during the year becomes exaggerated (compared to other continental areas) by the physically restricting barrier to the west.

3.2.2 Spring and Summer Conditions

The spring and summer months have the lowest percentage frequency (annual minimum) of mixing heights less than 200 m (Fig. 3.3 a). Similarily, frequencies of mixing heights less than 600 m (Fig. 3.3 b) decrease from just over 20% in spring to less than 8% in summer. Moreover, the frequencies of mixing heights greater than 2000 m are the maximum for all of Canada during these seasons (Appendix C - Part 2, Tables 9 and 10). In this mixing height category (Fig. 3.3 c) frequency values of almost 40% in spring increase to over 55% in the summer.

There are several inter-related factors responsible for the improvement in vertical diffusion across the region at this time:

(i) Spring:

First of all, the upper flow gradually changes from the mean northwesterly direction in winter to a strong zonal flow in spring. These westerly winds carry Pacific short-wave troughs and milder airmasses in rapid succession across the mountains. Aided by low-level cold air injections to the lee of the ranges, intense spring storms often develop across the region. As the season progresses, the frequency and intensity of an upper wind component normal to the mountains increases. This results in greater lee subsidence, and the mild Pacific airmasses are warmed to even higher temperatures as they descend the barrier. By early summer, an upper ridge is established along the Alberta - B.C. border, and a mean westerly diffluent flow aloft predominates over the region.

Because of the above meteorological factors, spring is relatively short along the southern foothills and plains to the lee of the Rockies. Winter normally persists into early March while summer arrives by the end of May. Rapid transitions take place during this period. The changes in the upper flow and resultant large-scale subsidence warming reinforce the intense surface heating generated by increased hours of sunlight. Surface temperatures rise rapidly in the order of 2^{o} to 4^{o}C daily.

At the same time, the snow and ice cover rapidly modify during this period. By the end of March, the snow cover is usually gone in southwestern Saskatchewan and southeastern Alberta. A dull brown dried grass surface with low reflectivity and a high thermal efficiency is exposed. In contrast northern and much of eastern Alberta remains snow covered until later in the period. (Higher elevations along the foothills also retain a snow cover).

The frequency patterns (Appendix A.I) of mixing heights below 600 m show a relatively higher percentage frequency of occurrence in these areas due to the radiational cooling and the modification of air above the residual snow pack. (Nocturnal radiation inversions are more intense and less likely to 'burn-off' during the day. The vertical temperature profile often reveals surface- or near surface-based inversions in these cases).

Another factor that contributes to the colder air and lower mixing heights to the north and east of the region is the gradual slope from the foothills to the plains. This graded relief results in cold air drainage towards these areas. Similarily, frost hollows at lower levels in irregular topography may produce large temperature variations over small horizontal distances. The coldest to the warmest maximum surface temperatures can vary as much as 10^{o} to 15^{o}C.

The combined thermal and reflective differences within the region cause variable mixing height statistics between the north and east, and the southwest. For example, mixing heights less than 600 m occur in over 25% of the cases in the northern and eastern sections of the region, while in direct contrast, southwestern Alberta and western Montana have a maximum frequency area of mixing heights greater than 2000 m. Frequency values of greater that 50% in spring increase to over 70% in the summer in this area.

(ii) Summer:

During the summer months, periodic short-wave troughs embedded in the westerly flow aloft travel across the mountains from the Pacific. These upper troughs are associated with relatively colder air at higher levels in the troposphere. In advance and along the leading edge of the cold air aloft (i.e. along the upper cold front) upper-level divergence and maximum upward vertical velocity occur through the atmosphere below.

At the same time, daytime surface temperatures increase and thermal instability develops over the heated land. This intense surface heating in conjunction with the upper cold troughs produces unstable equilibrium in the lower atmosphere. Instability exists whenever the prevailing environmental decrease of temperature with height exceeds the dry adiabatic lapse rate or about 1^{o}C per 100 m, but is less than 3.4^{o}C per 100 m. Under these circumstances, the atmosphere is unstable for either saturated or unsaturated air. (A prevailing lapse rate in excess of 3.4^{o}C per 100 m is extremely rare and restricted to a very shallow layer immediately above a strongly heated dry surface, such as desert sand or rock, when the sun is high on a clear day and the wind is light). When the above superadiabatic conditions occur, rising air remains warmer and lighter than the surroundings and continues upward. Vertical diffusion is a maximum and higher mixing heights or 'unlimited' mixing cases occur.

During the summer, the dry grassland and arid conditions present across southern Alberta and southwestern Saskatchewan result in very strong surface heating. Dry adiabatic lapse rates (usually confined to the lowest thousand metres of the atmosphere) can extend up to 3000 to 4000 m during periods of intense heating in these areas. (Over 70% of the cases have mixing heights greater than 2000 m along the southwestern foothills in the summer).

In the early part of the season, when excessive moisture is still available from spring runoff and evaporation from the lakes and rivers, extensive daytime cumulus clouds appear on a diurnal cycle. During this classical summertime state in Alberta, afternoon cumulus often build into towering cumulus or cumulonimbus, giving showers or thundershowers by evening. Periods of deep convection occur when intense surface heating coincides with an advancing upper trough. In these cases, thunderstorms often with hail and severe winds, penetrate through the tropopause. The period of maximum

convective instability in Alberta occurs in July, and corresponds to the period of maximum surface heating.

Another secondary process that generates instability in the region is convergence. The mean surface low pressure area over the Prairies at this time results in a net westerly to northwesterly downslope flow across the foothills. However, convergence against the Swan Hills in central Alberta or the Cypress Hills in southern sections of the region make these favoured areas for convection.

The westerly flow and unstable conditions prevalent during the spring and summer limits periods of low mixing heights. These conditions do, however, occur from time to time. They are usually associated with an easterly upslope surface wind component which occurs during a cold low. This is a closed cyclonic circulation with a cold core that extends through the troposphere. An occasional cold low will spin-off the main Alaska low and penetrate into the region during the spring and summer. A period of below normal maximum temperatures, extensive low-level stratus and large-scale precipitation can last over three to four days. In these cases, low mixing heights are common, although horizontal ventilation is generally good due to the stronger surface winds and turbulent mixing in the boundary layer.

The maximum cloud cover during the spring and summer seasons occurs in June. This is due not only to the more frequent cold lows at this time, but to the additional moisture available from spring runoff and evapotranspiration from early crops and vegetation. Spring and early summer storms are usually extensive while mid-summer storms are more localized and convective in nature.

While mixing heights are higher across the south, mixing heights from 400 to 1200 m are more common in the Peace River District, especially in the spring. One reason for this is the depression in the altitude of the Rockies just west of this area, that allows moist Pacific airmasses to penetrate across the divide without too great moisture loss through subsidence.

3.2.3 Fall and Winter Conditions

A significant change in the frequency patterns (Appendix A.I) of the lowest mixing height ranges takes place during the fall. By winter, a pronounced trough of higher frequencies extends across the region from the northwest. This trough is an extension of the deep Mackenzie Valley trough where frequencies of over 50% occur.

In the fall, a weak ridge of lower frequencies is still evident along the southwest foothills for mixing heights less than 200 m. In winter, this feature virtually disappears. The frequencies of mixing heights less than 200 m and 600 m (Fig. 3.3 a and b, respectively) are much greater than the corresponding spring and summer values. In the winter, a marked increase to over 85% occurs for mixing heights less than 600 m. At the same time, frequencies of mixing heights greater than 2000 m drop from over 55% in the summer to less than 15% in the fall, and near zero in the winter. In fact, in the latter season, the frequencies of in-

dividual levels above 1000 m are less than 2% (Appendix B, Table 3.1).

Like most continental climates, the transition from summer to winter is fairly rapid in this region. In the case of the area to the lee of the Rockies, however, other factors hasten the advance of winter or exaggerate the extremes that occur. These factors include (i) the direct Arctic passage, and (ii) the mild "Chinook" conditions.

(i) The mean surface pressure pattern at this time of the year is a ridge of high pressure from the Arctic Ocean to the Prairies, between the Gulf of Alaska lows to the west and the Hudson Bay lows to the east. Cold Arctic air advances along a direct path into the region essentially unchanged from its original source region characteristics. Furthermore, the mountains retain the deepening cold air and prevent its westward dilution or its modification by the ocean.

At the same time, there is a shift in the upper flow from a mean westerly direction in the summer to a strong northwesterly flow in winter. During the transition period, Pacific shortwaves embedded in the westerly flow interchange with cold troughs rotating from the north in the cyclonic flow around a developing Arctic vortex.

Warm, moist air from the Pacific descends over the mountains in the westerly flow and alternates with cold outbreaks from the north. Lee cyclogenesis occurs in the process. The boundary between the cold Arctic air and mild Pacific air moves north and south between Wyoming and the NWT, and gradually drops southward as winter approaches. At the interface of this boundary, intense Prairie storms (or blizzards) frequently occur. These storms result in a widespread snow cover across the northern and eastern sections of the region by mid-November in most years. A corresponding change in the surface thermal and reflective characteristics takes place in these areas.

In addition to the cloud cover generated by these systems, moisture available through evaporation from lakes and rivers before freeze-over reduces daytime insolation. This reduction is compounded by the shortened days and the highly reflective snow cover. Surface temperatures drop sharply overnight and rarely recover during the day over northern and central sections of the region. When winter arrives, the cold air becomes firmly established against the mountains in the outflow from the quasistationary high pressure ridge through the Prairies. At the same time, the lakes are frozen, the ground is covered with snow, the sun angle is lowest, and incoming solar radiation is a minimum (January 15th to the 25th is the coldest period for the region). There is a marked albedo gradient eastward from the forested foothills to the uniformly snow covered plains.

The intense Arctic surface or near surface-based inversion present over the region becomes an almost permanent feature in the winter. Pacific trowals (troughs of warm air aloft) that cross the mountains or come over the upper ridge from Alaska generally travel along the baroclinic zone established along the divide and override the colder surface air along the foothills and plains to the east. Periodically, these systems set off blizzard conditions through central and southern Alberta and southern Saskatchewan.

Northeastern sections, however, are under the influence of the stagnating ridge of high pressure, and the deepest, coldest air. As a result, these sections have the least cloud cover, but the coldest daytime surface temperatures due to the length of the night and the intense radiational cooling. Mixing heights in the area are correspondingly lower in the winter. (From the frequency patterns in Appendix A.I, frequencies of 80 - 90% occur for heights below 400 m).

These factors support the observed high frequency of low mixing heights during this period. An annual maximum (over 85%) occurs for mixing heights below 600 m (Fig. 3.3 b). For afternoon mixing heights above 600 m, the frequencies drop off radically over the entire region. Only the extreme southwestern sections have frequencies greater than 4% (Appendix A.I).

This brings the discussion to the area within the region that warrants special attention. The second factor that exaggerates the surface temperature extremes in fall and winter, and contributes to the highest mixing heights compared to the other regions throughout the year is observed mainly across the south.

(ii) The "chinook" is broadly defined as a warm, dry wind descending the leeward side of the mountains (Brinkman and Ashwell, 1968). This condition exists along the southwestern sections of the Prairies (immediately east of the highest elevations in the Canadian Rockies) whenever upper winds with a moderate to strong westerly component impact the range. As air descends the slopes, it warms at a rate of about $1^{o}C/100$ m. The intensity and horizontal extent of this modification varies with the strength and the angle of incidence of the upper flow.

Longley (1967) observed that chinooks are not restricted to the winter season but the effects are most pronounced at that time. Surface temperatures associated with the warming wind are usually about $5^{o}C$ although they may be as great as $25^{o}C$. Fig. 3.4 shows the number of days with maximum temperatures greater than $4^{o}C$ during the winter and is a good indicator of the 'chinook belt' across the region. Its influence is most profound in the area south of Red Deer in southern Alberta to northern Montana (Marsh 1965, Longley, 1967). The Leahey and Davies report (1977) describes the ideal chinook as consisting of (a) a large scale advection components involving the exchange of airmasses and subsidence in the lee of the mountains (Osmon 1941, McCabe 1962, Brinkman 1969), and (b) mesoscale wave component involving the excitation of gravity waves by the mountains. (NOTE: Periods of anomalous warming can also be associated with the northward advection of tropical air (Leahey and Davies, 1977). For example, the case of a digging trough along the Pacific coast may place Alberta in a strong southerly flow carrying warm air from as far south as the Gulf of Mexico.)

As warm subsided air passes to the east, two processes modify the air closest to the surface. First of all, contact with the cold surface or sublimation of the snow cools the warmer air. A net 'chinook inversion' results in the lowest layers above the surface. Areas on the fringes of the chinook belt, such as Edmonton, usually have extensive, highly reflective snow covers compared to areas further south. Around Calgary and Lethbridge, for example, the generally treeless landscape has less snow accumulation. Over exposed, dried grass surfaces in these areas, unstable lapse conditions

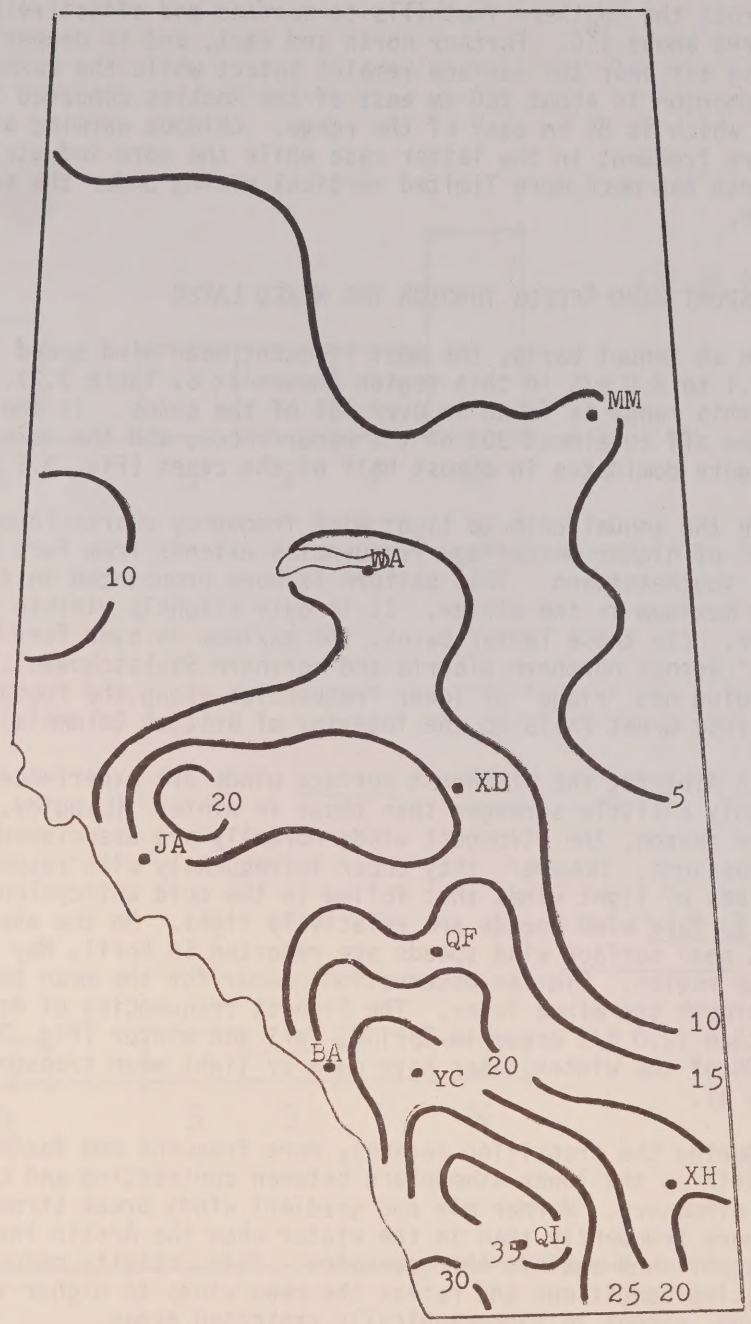


FIG. 3.4 Mean Number of Days With Chinooks (i.e., maximum temperatures greater than 4°C) During the Winter (Dec, Jan, Feb) (Longley, 1967)

may occur during periods of anomalous warming. In the second case, the warm air and stronger winds associated with a chinook are generally strong enough across the southern foothills to surface and effectively raise the temperatures above 4°C. Further north and east, and in deeper valleys, the cold, dense air near the surface remains intact while the warmer air moves aloft. Edmonton is about 280 km east of the Rockies compared to Calgary in the south which is 80 km east of the range. Chinook warming at the surface is far more frequent in the latter case while the more industrialized city to the north has much more limited vertical mixing under the same synoptic conditions.

3.3 MEAN TRANSPORT WIND SPEEDS THROUGH THE MIXED LAYER

On an annual basis, the most frequent mean wind speed range occurs between 4.1 to 8.0 m/s in this region (Appendix B, Table 3.2). From spring to fall, this range is found in over 40% of the cases. In the winter, this range drops off to almost 30% of the occurrences, and the calm to light wind category dominates in almost half of the cases (Fig. 3.5 a).

On the annual calm to light wind frequency charts (Appendix A.I) a 'trough' of higher percentage frequencies extends from Fort Nelson to Edmonton, southeastward. This pattern is more pronounced in the fall and reaches a maximum in the winter. It is only slightly visible in spring and summer. (In these latter cases, the maximum is over Fort Nelson with a 'trough' across northern Alberta and northern Saskatchewan). There is a corresponding net 'ridge' of lower frequencies along the foothills of southern Alberta (from Great Falls to the interior of British Columbia).

In Alberta, the strongest surface winds are experienced in spring and are only a little stronger than those in winter (Longley, 1967). In the latter season, the strongest winds normally are associated with cold frontal passages. However, they occur infrequently with respect to the long periods of light winds that follow in the cold anticyclones. Thus, the mean surface wind speeds are relatively light. On the average, the strongest mean surface wind speeds are reported in April, May and October across the region. Similar observations occur for the mean transport wind speeds through the mixed layer. The highest frequencies of mean winds greater than 12.0 m/s occur in spring, fall and winter (Fig. 3.5 b) and almost 50% of the winter cases have calm or light mean transport wind speeds (Fig. 3.5 a).

During the transition seasons, more frequent and faster moving systems stir up the lower atmosphere between contrasting and constantly changing airmasses. Warmer air and gradient winds break through to the surface more frequently than in the winter when the Arctic inversion is firmly established against the mountains. This activity reduces the periods of stagnating conditions and raises the mean winds to higher values on the average, except in topographically protected areas.

In the summer, the mean surface and synoptic pressure patterns are weak. However, higher airmass temperatures, greater surface heating and peak convective overturning mix the lower atmosphere and contribute to relatively high mean wind speeds through the mixing layer. Mechanical

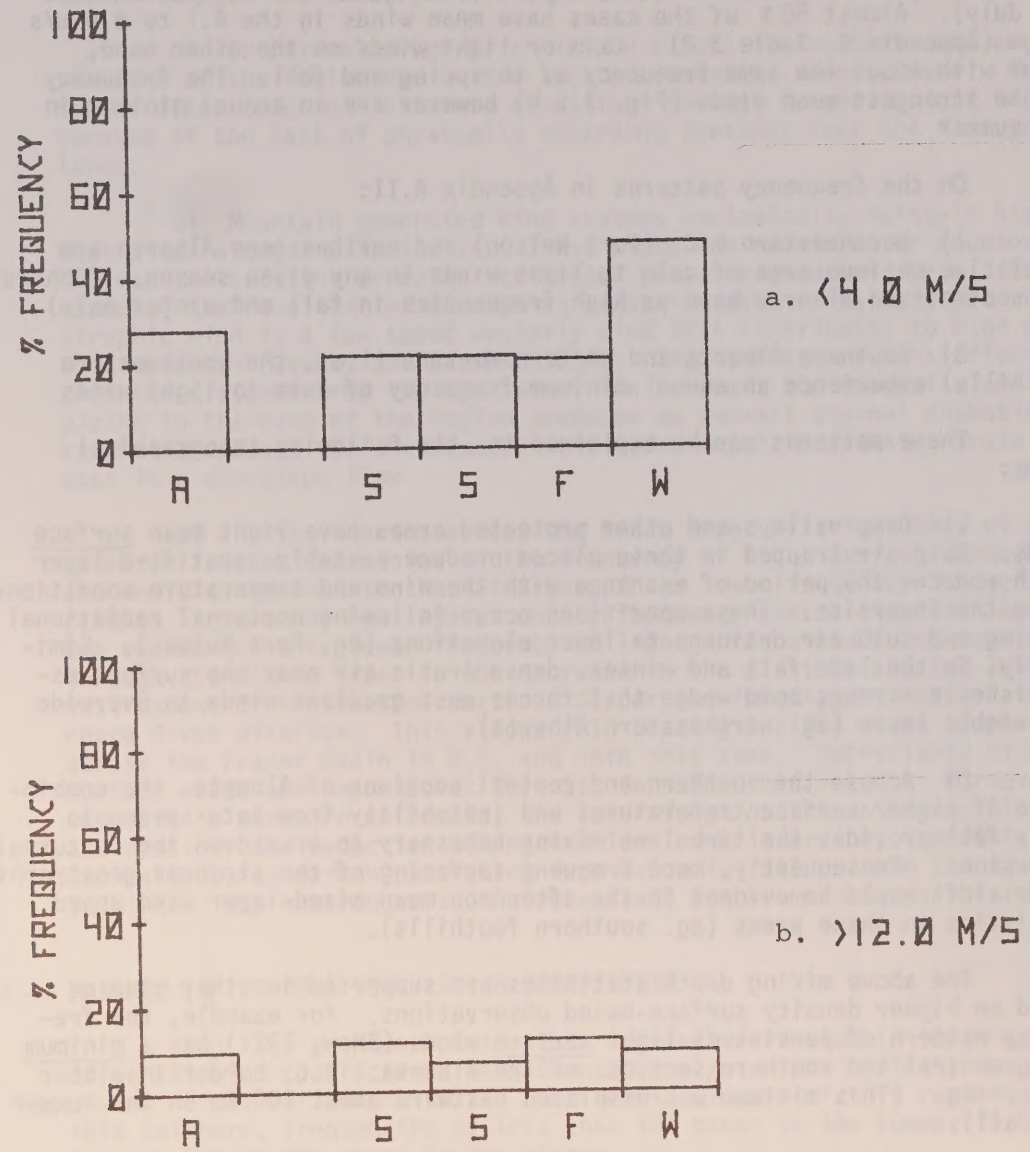


FIG. 3.5 Annual and Seasonal Frequencies of Occurrence of Mean Wind Speeds Through the Mixing Layer (m/s) for the Lee of the Rockies Region

mixing and gusty surface winds associated with convection also contribute to dispersion through the boundary layer. (Peak gusts are highest in June and July). Almost 50 % of the cases have mean winds in the 4.1 to 8.0 m/s range (Appendix B, Table 3.2). Calm or light winds on the other hand, occur with about the same frequency as in spring and fall. The frequency of the strongest mean winds (Fig. 3.5 b) however are an annual minimum in the summer.

On the frequency patterns in Appendix A.II:

1) Northeastern B.C. (Fort Nelson) and northwestern Alberta are a relative maximum area of calm to light winds in any given season. (Central and southestern Alberta have as high frequencies in fall and winter only).

2) Southern Alberta and western Montana (i.e., the southwestern foothills) experience an annual minimum frequency of calm to light winds.

These patterns can be explained in the following topographical terms:

1) Deep valleys and other protected areas have light mean surface winds. Cold air trapped in these places produce a stably stratified layer which reduces the period of exchange with the wind and temperature conditions above the inversion. These conditions occur following nocturnal radiational cooling and cold air drainage to lower elevations (eg. Fort Nelson). Similarily, in the late fall and winter, dense Arctic air near the surface establishes a strong, cold wedge that forces most gradient winds to override the stable layer (eg. northeastern Alberta).

2) Across the southern and central sections of Alberta, the combination of higher surface temperatures and instability from late spring to early fall provides the turbulent mixing necessary to breakdown the nocturnal inversions. Consequently, more frequent surfacing of the stronger geostrophic winds aloft would be evident in the afternoon mean mixed-layer wind speed statistics in these areas (eg. southern foothills).

The above mixing depth statistics are supported in other studies based on higher density surface-based observations. For example, the frequency pattern of persistent light surface winds (Shaw, 1971) has a minimum along central and southern sections of the Alberta - B.C. border in winter and spring. (This minimum was displaced eastward about 200 km in the summer and fall).

Some of the regional differences in wind speeds may be explained as follows:

a) Across the south, the effects of the Chinook increase the mean mixed-layer wind speeds and surface wind speeds over that farther to the north and east. (The effects of the Chinooks on the winds are evident as far north as Coronation and as far east as Estevan, Saskatchewan (Longley, 1967)).

b) Higher wind speeds occur across the south due to the channelling of warm Pacific air through the mountain passes. For example, channelling through Crowsnest Pass in the extreme southwestern section of the region

would reinforce the mean wind speed through the mixing layer in areas immediately to the east (Pincher Creek to Lethbridge).

c) Frictional drag is a minimum across the southern and eastern sections of the region due to the lack of extensive forest cover. Intense storms often touch off blizzard conditions through Coronation and Vermilion because of the lack of physically retarding features over the flat grasslands.

d) Mountain generated wind systems periodically maintain higher mean winds along the foothills. These winds can reinforce or counterbalance the existing synoptic horizontal pressure gradient force. For example, the resultant of an evening katabatic wind in Calgary and the geostrophic wind is a low speed westerly wind that contributes to high pollution episodes (Leahey and Davies, 1977). The strength of this effect varies with the distance from the mountains. In general, the gradual slope to the plains in the east of the region produces an overall diurnal anabatic and katabatic effect. In the summer, the colder mountain climates drain to the east in a downslope flow.

e) Further north, across the Peace River district, Shaw et al (1971) noted an interesting minima in the frequency of light surface winds. This are would correspond to the extension of the lower frequency 'ridge' of calm to light winds that appear on the frequency charts (Appendix A.II). One reason for this lower frequency of light surface winds and mean winds through the mixing layer is the decrease in the altitude and the less east-west extent of the Rockies north of Jasper and immediately west of the Peace River district. This allows rain bearing Pacific winds to pentrate across the Fraser Basin in B.C. and into this area. Appreciably higher surface winds are reported at Fort St. John for this reason. Moreover, the exposure to northern outbreaks, the lower friction across Lesser Slave Lake and possibly the reduction of intense low-level inversions immediately above the lake due to warmth pentrating from below in fall or even through the ice in winter may contribute to the relatively higher mean winds observed.

3.4 MAXIMUM (AFTERNOON) VENTILATION COEFFICIENT

Fig. 3.6 a shows considerable seasonal variation in the frequencies of ventilation coefficients less than 3000 m^2/s. This reflects the general mixing height variations in the continental climate of this region. In this category, frequencies of less than 10% occur in the summer in contrast to over 75% of the cases in the winter.

In Fig. 3.6 c the frequency of ventilation coefficients greater than 11,000 m^2/s is a maximum in the summer. (This frequency of over 55% is also the maximum for all of Canada (Appendix C - Part 2, Table 26)). These frequencies plunge to near 5% in the winter. The winter frequency pattern (Appendix A.III) of ventilation coefficients greater than 11,000 m^2/s shows that cases in this category are confined to the southwestern foothills section of the region. This is largely the result of the chinook phenomena. (In a preliminary study of the effects of mountain generated wind systems on air pollution levels in Calgary, it was concluded that the chinook does not have an adverse effect on Calgary's air quality (Leahey and Davies, 1977)).

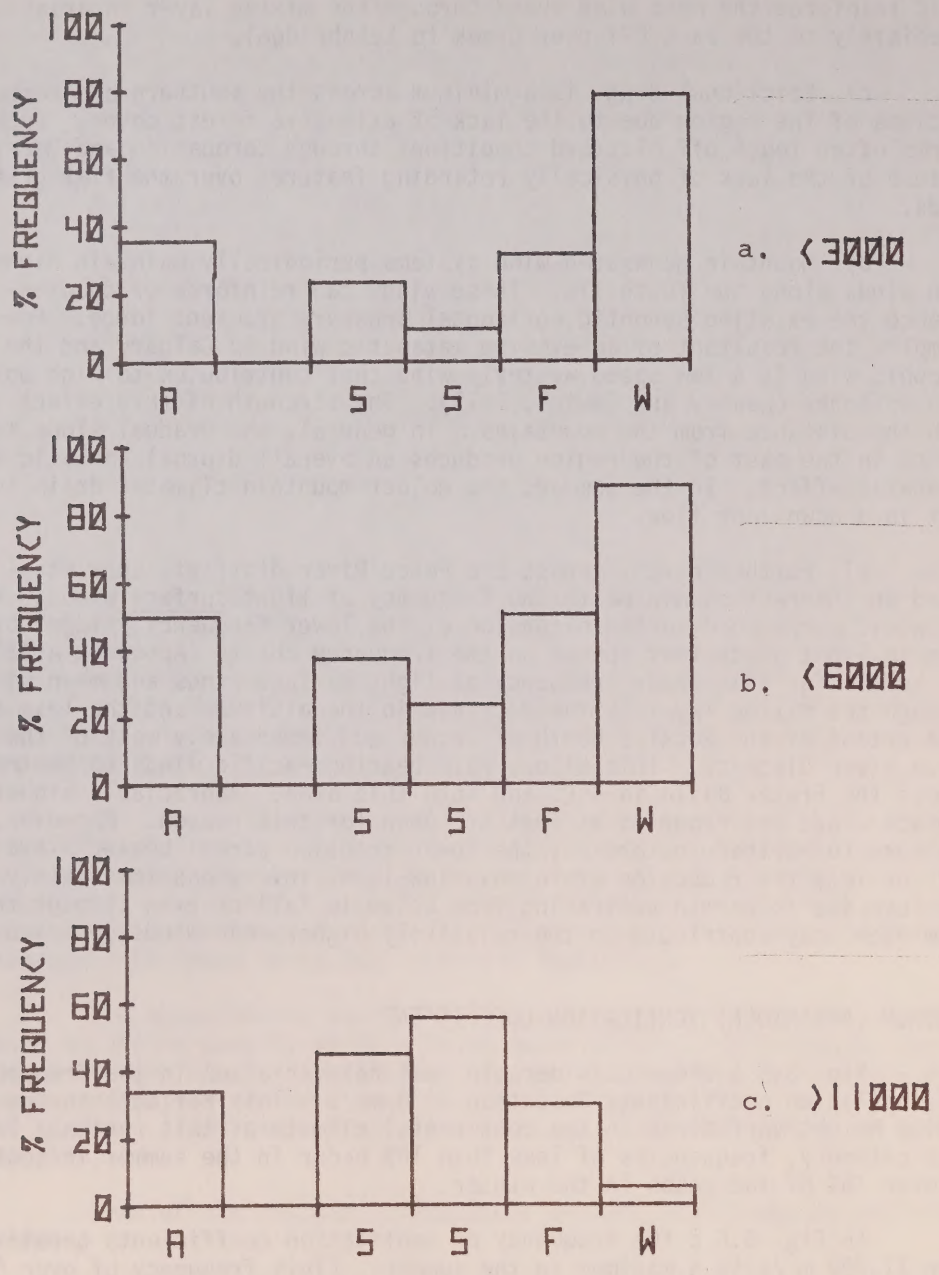


FIG. 3.6 Annual and Seasonal Frequencies of Occurrence of Afternoon Ventilation Coefficients (m^2/s) for the Lee of the Rockies Region

The reverse pattern occurs for frequencies of ventilation coefficients less than 1000 m^2/s. In the fall and winter, a maximum frequency 'trough' extends along the foothills reflecting the presence of the stagnating high pressure ridge and the cold air inversion in the lowest levels of the atmosphere. Almost 50% of the cases occur in this lowest ventilation category.

3.5 CONCLUSIONS

This is a region of contrast. During most of the year, from spring to fall, the mountains to the west provide generally good horizontal and vertical diffusion over the region. In the winter, the opposite is true.

Within the region, physical variations between the north and south give generally better mixing conditions to southern foothills than to the heavily industrialized northern sector.

PRAIRIES

CHAPTER 4

CHAPTER 4

PRAIRIES REGION

(Saskatchewan, Southern Manitoba)

4.1 INTRODUCTION

Several distinctive characteristics of the interior continental plains define the seasonal pollution potential climatology of this region. The most dominant climate control is the location along a broad, relatively flat corridor from the Arctic Ocean to the Gulf of Mexico. This position allows maximum exchange over the region between widely contrasting airmasses. The Rocky Mountains to the west physically block Arctic outbreaks and channel the cold, dense air towards the lower elevations of the Prairies. At the same time, the Western Cordillera prevent moisture laden Pacific airmasses from greatly modifying the interior.

The Prairies region covers a generally flat, treeless grassland on a gentle slope from the western foothills to near sea-level of the Hudson Bay and eastern Manitoba (Fig. 4.1). Only minor uplands rise above the surrounding plain and two large lakes modify local areas in southern Manitoba. However, in general there are few natural physical features within the region sufficiently prominent to materially affect the regional climate.

The two radiosonde stations available to represent the boundary layer climate of the interior Prairies are The Pas and Bismark (see Appendix D).

4.2 MAXIMUM (AFTERNOON) MIXING HEIGHTS

4.2.1 General Characteristics

The seasonal frequency distribution of mixing heights shown in Fig. 4.2 reflects the continental character of the region. Frequencies greater than 25% in the summer drop to zero in the winter. In fact, in the winter the frequencies of mixing heights above 1000 m is near zero.

In the climatology of surface-based inversions in Canada (Munn et al, 1970) Manitoba and Saskatchewan display a typical continental climate in which a nocturnal inversion is replaced by a dry adiabatic lapse condition during mid-day. This diurnal cycle is particularly evident from late spring to early fall when daytime heating is a maximum. Relatively low frequencies of mixing heights less than 200 m (Fig. 4.3 a) are observed. The seasonal frequency distribution of mixing heights below 600 m (Fig. 4.3 b) shows that summer has the lowest frequency. In the fall, this increases to over 40%. In winter, over 90% of the occurrences are below this limited mixing level.

The basic continental character of the region is reinforced by the homogeneous nature of the Prairie grassland. There are very few deep valleys or wooded areas to cause large-scale differential heating patterns or anomalies in the wind systems. Also, the Prairies region is shielded from the influence of the Pacific Ocean to the west by the Rocky Mountain range. The proximity of the Hudson Bay to the northeast, however, is not critical in terms of mixing height statistics since the flow is seldom from that direction. The

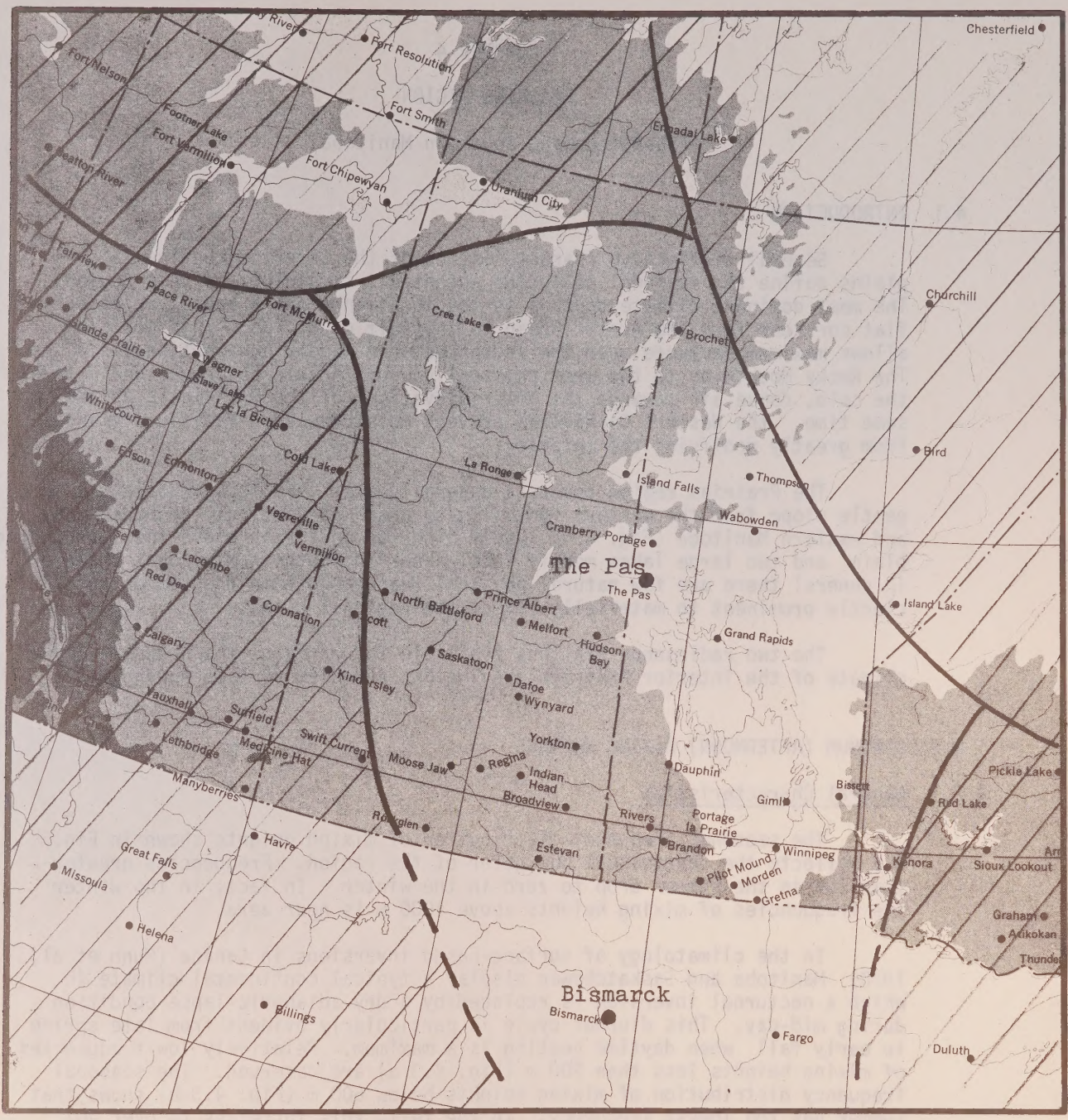


FIG. 4.1
PRAIRIES

● - rawinsonde station sites

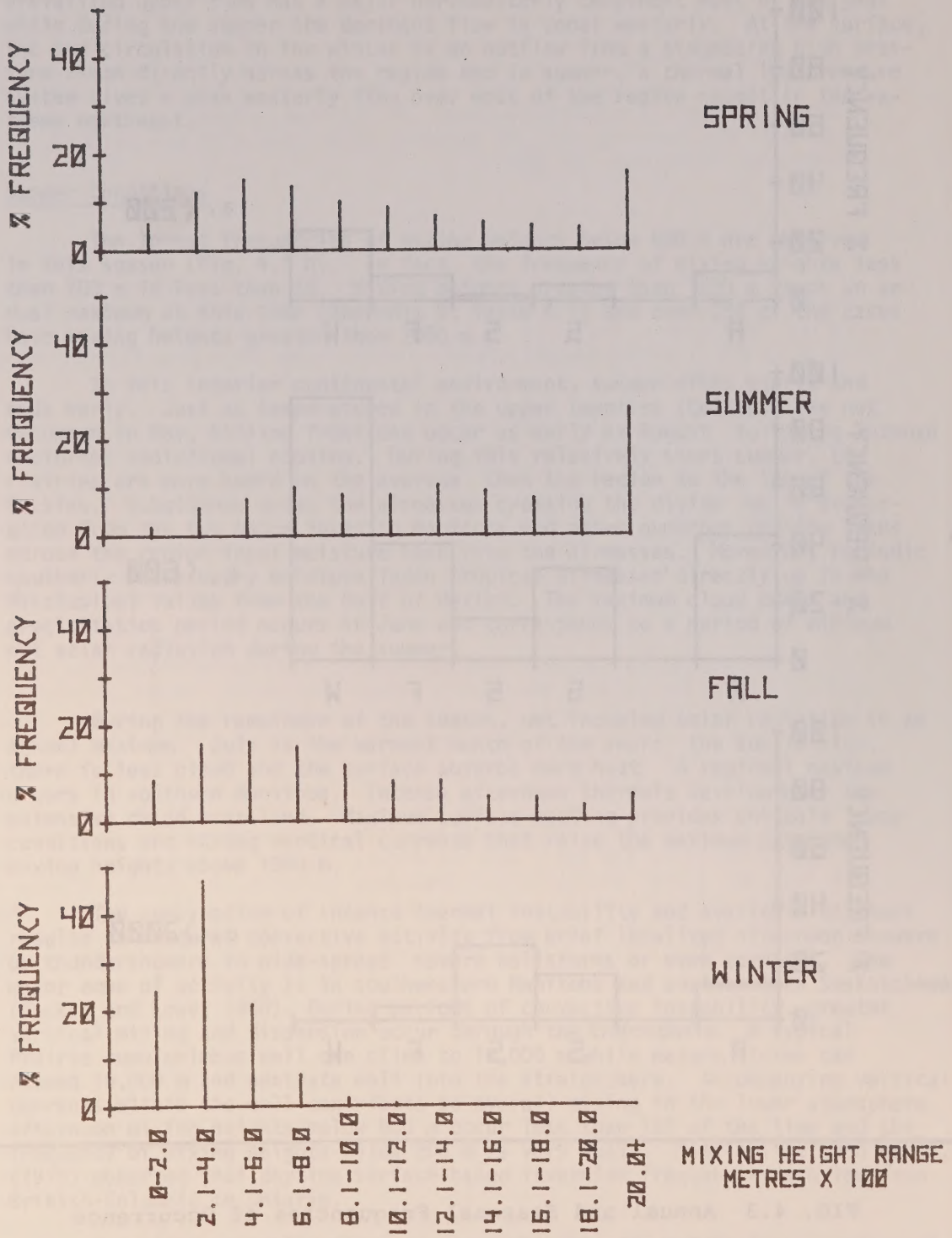


FIG. 4.2 SEASONAL FREQUENCY HISTOGRAMS OF SPECIFIED MAXIMUM MIXING HEIGHTS.

REGION: PRAIRIES

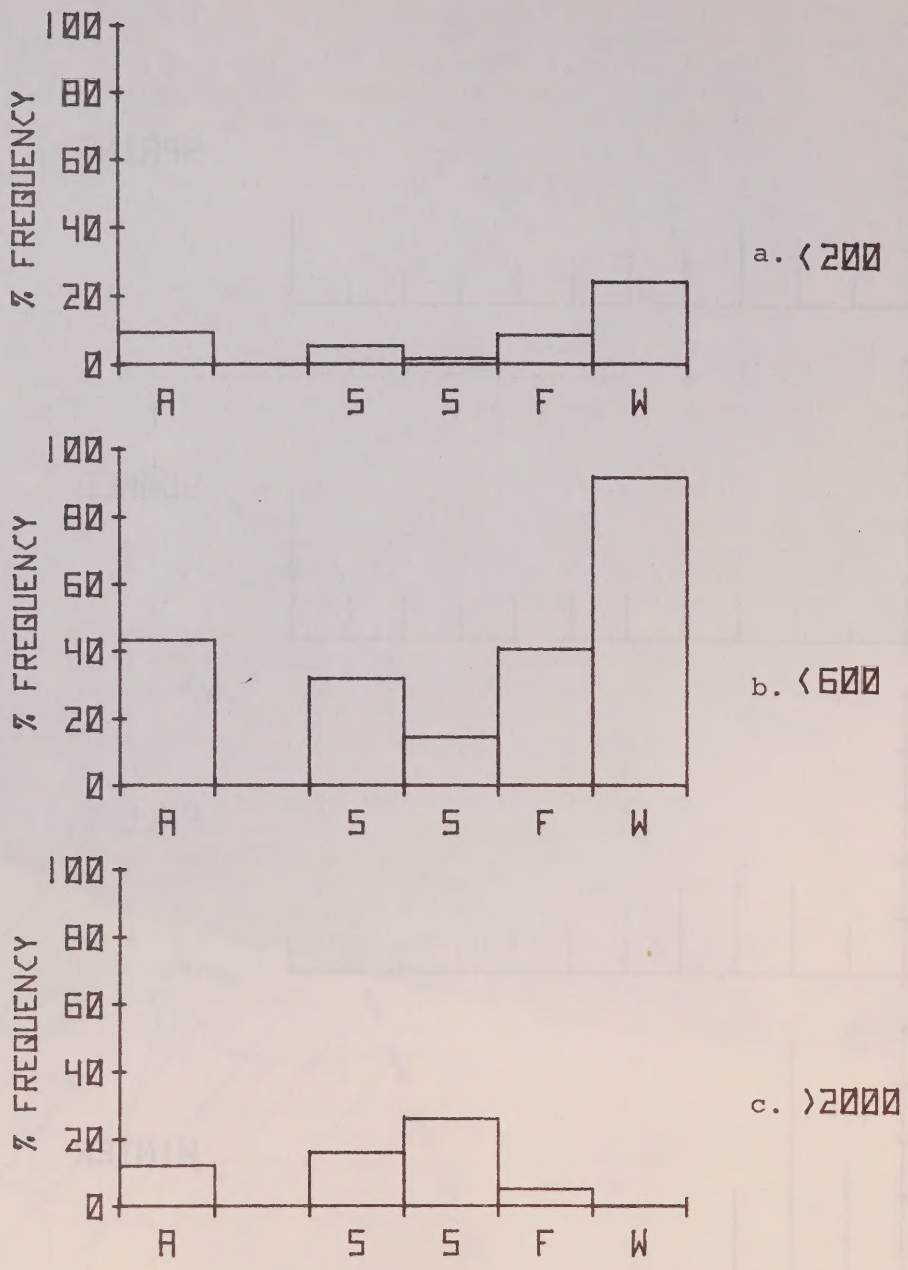


FIG. 4.3 Annual and Seasonal Frequencies of Occurrence of Maximum (Afternoon) Mixing Heights (m) for the Prairies Region

prevailing upper flow has a major northwesterly component most of the year while during the summer the dominant flow is zonal westerly. At the surface, the net circulation in the winter is an outflow from a stagnating high pressure ridge directly across the region and in summer, a thermal low pressure system gives a mean westerly flow over most of the region except in the extreme northeast.

4.2.2 Summer Conditions

The lowest frequencies of mixing heights below 600 m are observed in this season (Fig. 4.3 b). In fact, the frequency of mixing heights less than 200 m is less than 2%. Mixing heights greater than 1000 m reach an annual maximum at this time (Appendix B, Table 4.1) and over 25% of the cases have mixing heights greater than 2000 m.

In this interior continental environment, summer often starts and ends early. Just as temperatures in the upper twenties (Celcius) are not uncommon in May, killing frost can occur as early as August following intense nocturnal radiational cooling. During this relatively short summer, the Prairies are more humid on the average than the region to the lee of the Rockies. Subsidence dries the airmasses crossing the divide while evaporation from the two major lakes in Manitoba and other numerous shallow lakes across the region input moisture back into the airmasses. Moreover, periodic southerly flows carry moisture laden tropical airmasses directly up in the Mississippi Valley from the Gulf of Mexico. The maximum cloud cover and precipitation period occurs in June and corresponds to a period of minimum net solar radiation during the summer.

During the remainder of the season, net incoming solar radiation is an annual maximum. July is the warmest month of the year: the sun is high, there is less cloud and the surface absorbs more heat. A regional maximum occurs in southern Manitoba. Intense afternoon thermals develop over the extensive dried grassland. Maximum surface-heating provides unstable lapse conditions and strong vertical currents that raise the maximum afternoon mixing heights above 1000 m.

The combination of intense thermal instability and available moisture results in frequent convective activity from brief localized afternoon showers or thundershowers to wide-spread severe hailstorms or even tornados. The major zone of activity is in southwestern Manitoba and southeastern Saskatchewan (Mackay and Lowe, 1960). During periods of convective instability, greater vertical mixing and dispersion occur through the troposphere. A typical Prairie cumulonimbus cell can climb to 10,000 m while mature storms can exceed 15,000 m and pentrate well into the stratosphere. Accompanying vertical currents within the cell contribute to overall mixing in the lower atmosphere. Afternoon mixing heights below 600 m occur less than 15% of the time and the frequency of mixing heights below 200 m is very small. Similarily, Munn et al, (1970) observed that daytime surface-based inversion frequencies are low from British Columbia to Ontario.

Under the generally clear summer night skies in the Prairies, nocturnal radiation inversions usually develop. In most cases, these inversions dissipate with surface-heating by noon local time. The rare cases when they do

persist occur with cold advection or intense radiational cooling followed by overcast stratocumulus which prevents sunshine from penetrating through the cloud deck and heating the surface. This situation occurs locally in an onshore flow from a relatively deep or large lake. In these cases, cold air advection from over the lake in a lake-breeze or with the synoptic flow suppresses intense surface-heating. In addition, advection fog or stratus from over the lake may cut off incoming solar radiation and maintain low-level inversions throughout the day.

4.2.3 Winter Conditions

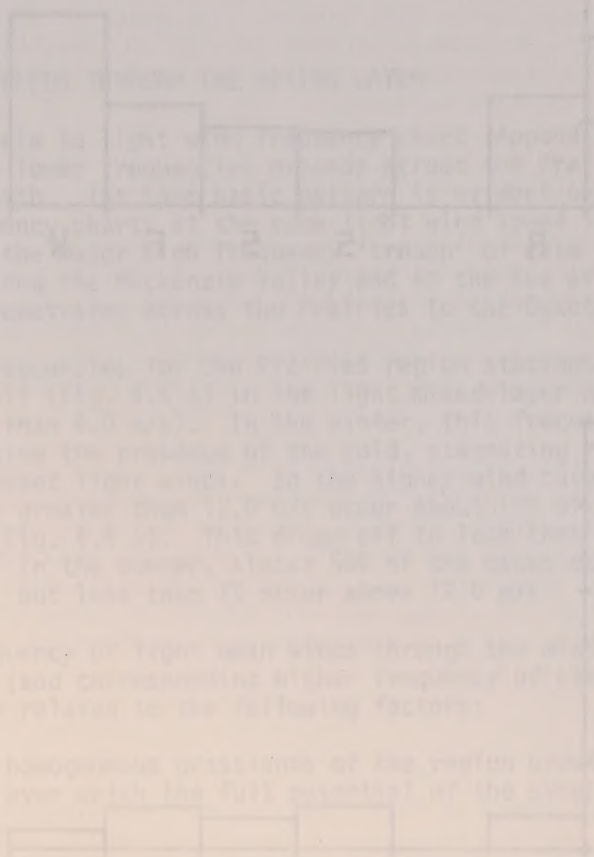
Reflecting the true continental character of the interior plains, the mixing height frequencies for levels below 600 m reach an annual maximum during the winter. From Fig. 4.2, the most frequent heights occur in the 200 m to 400 m mixing height ranges. Frequencies of mixing heights above 1000 m are negligible.

At this time, the mean position of the high pressure ridge at the surface is in a direct line from the Arctic source region, through the Mackenzie Valley and the central Prairies to the Dakotas to the south. The stagnating continental Arctic airmass is firmly established over the region by December, and usually remains until the end of March. Radiational cooling and high reflectivity from the snow (as well as an extensive cloud cover across the south) reduce the little insolation available and maintain the cold Arctic airmass characteristics. This is manifested in the high frequency of low-level inversion across the region.

Periodically, systems from the Pacific will carry milder air and moisture into the region, especially across the south. Normally, the milder air overrides the cold surface layer or is modified through surface contact by the time it arrives. In well-developed systems or strong southerly flows aloft, the warmer air may surface. (Variability of the daily maximum surface temperature about the mean is greatest in the winter for the Prairies). These intense circulations relieve periods of severely limited mixing and maintain slightly better diffusion over the southern Prairies compared to upslope regions to the west and sub-Arctic regions to the northeast. On the fall and winter mixing height frequency patterns for mixing heights less than 200 m (Appendix A.1) between a net high frequency 'trough' over the Hudson Bay to the east and another to the lee of the Rockies in the west, a net 'ridge' of relatively lower frequency values extends across the region.

4.2.4 Spring and Fall Conditions

Spring in the Prairies is very short. The transition from the winter snow and ice cover to good surface-heating by the end of May (across the south) results in rapidly increasing frequencies of higher mixing heights. Frequencies of mixing heights below 600 m decrease from over 90% in winter to near 30% in the spring (Fig. 4.3 b). Meanwhile, frequencies of mixing heights greater than 2000 m increase to over 15% (Fig. 4.3 c). In the fall the reverse process takes place as the cold Arctic or maritime Arctic outbreaks increase. The frequencies of mixing heights below 600 m increase to over 40% while those greater than 2000 m decrease from over 25% in the summer to around 5% at this time.



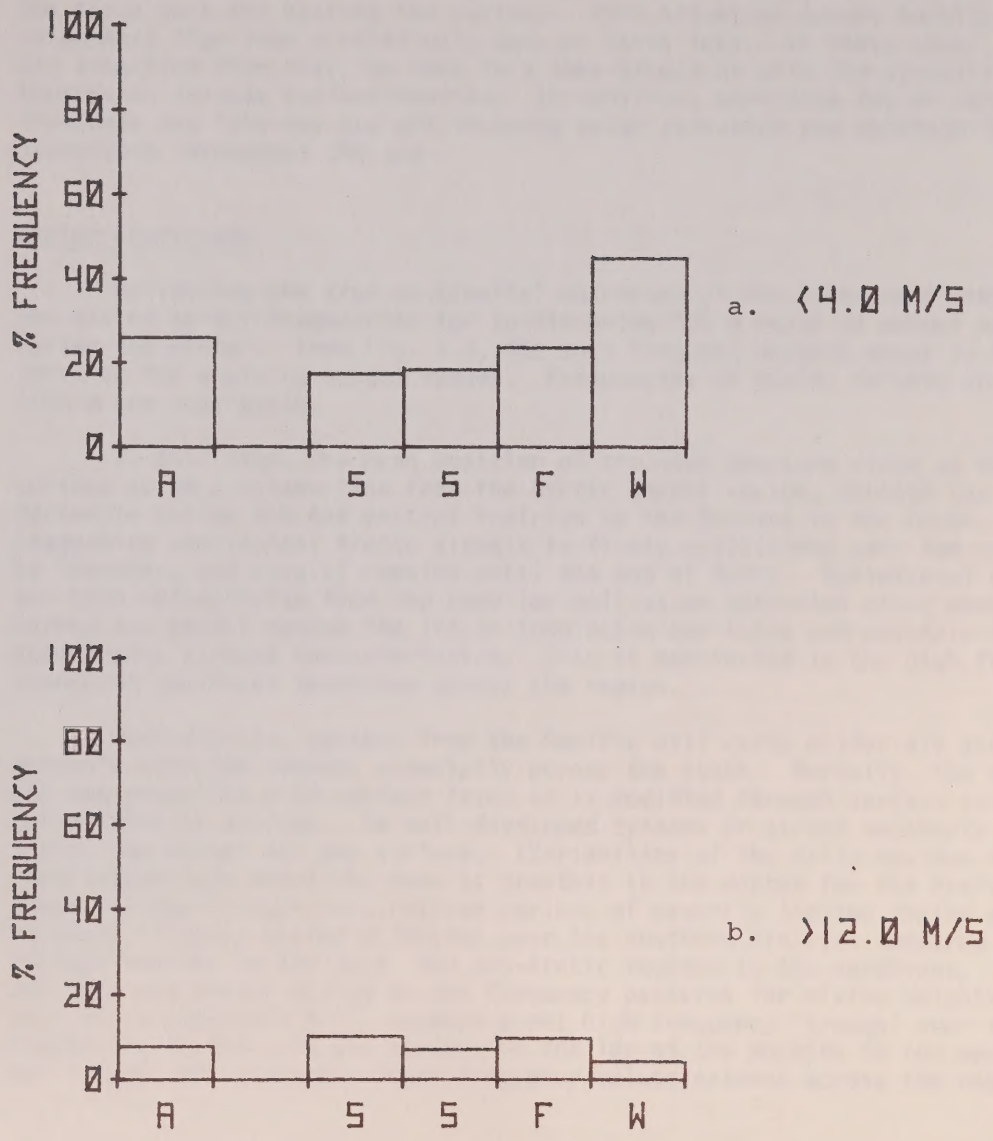


FIG. 4.4 Annual and Seasonal Frequencies of Occurrence of Mean Wind Speeds Through the Mixing Layer (m/s) for the Prairies Region

During the transition periods, changes in the upper flow pattern result in an increased frequency of low pressure systems of Pacific origin and the greatest difference in properties of contrasting airmasses. Spring storms across the Prairies are usually fast moving systems with warm air frequently surfacing across the south. (April is the stormiest month of the year, according to mean climatic studies). In the fall, frequent but slower moving systems travel across the region and usually are followed by cold outbreaks that pentrate further south as the season progresses. Due to the presence of the cold air for longer periods between the systems, the mixing heights are correspondingly more frequent below 600 m than in spring.

4.3 MEAN TRANSPORT WIND SPEEDS THROUGH THE MIXING LAYER

On the annual calm to light wind frequency chart (Appendix A.II) a 'ridge' of relatively lower frequencies extends across the Prairies to the barrens in the north. The same basic pattern is evident on the spring, summer and fall frequency charts at the same light wind speed level. In the winter, however, the major high frequency 'trough' of calm to light winds that extends along the Mackenzie Valley and to the lee of the Rockies through Alberta now penetrates across the Prairies to the Dakotas.

The average frequencies for the Prairies region stations vary around 20% from spring to fall (Fig. 4.4 a) in the light mixed-layer wind speed category (i.e., less than 4.0 m/s). In the winter, this frequency increases to almost 45% reflecting the presence of the cold, stagnating ridge of high pressure and its inherent light winds. In the higher wind categories, mean transport wind speeds greater than 12.0 m/s occur about 10% of the time in the spring and fall (Fig. 4.4 b). This drops off to less than 5% of the cases in the winter. In the summer, almost 50% of the cases occur in the 4.1 to 8.0 m/s range but less than 7% occur above 12.0 m/s.

The lower frequency of light mean winds through the mixing layer in the spring and fall (and corresponding higher frequency of winds greater than 12.0 m/s) may be related to the following factors:

1) The flat, homogeneous grasslands of the region provide an almost frictionless surface over which the full potential of the synoptic gradient wind may be realized.

2) Convective instability (over the snow-free surfaces) produces net vertical and horizontal mixing through the boundary layer and reduces extended periods of light surface winds.

3) The rapid motion and strong circulations associated with spring systems maintains a higher level of mean wind speeds through the mixing layer.

4) The mean northwesterly cyclonic gradient often places the Prairies in a strong downslope surface flow following the passage of systems into the Hudson Bay.

During the summertime, weak pressure patterns and upper flows extend over the Prairies and well-developed frontal systems are infrequent. This

lack of activity reduces the frequencies of mean wind speeds greater than 12.0 m/s. At the same time, however, the most frequent wind speeds are not calm. Almost 75% of the cases occur between 4.1 to 12.0 m/s (Appendix B, Table 4.2). The main factor responsible for these higher mean winds in spite of the weak gradient is the intense surface heating. Peak convective instability gives the highest annual mixing heights, strongest surface wind speeds (peak gusts) and considerable turbulent mixing through the boundary layer.

The high frequency of calm to light mean wind speeds through the mixing layer in the winter is related to the mean position of the high pressure ridge during this season. The presence of the cold Arctic inversion for long periods between systems results in frequent 'calms' over the region. The annual minimum frequency of winds greater than 12.0 m/s also occurs in winter for the same reasons.

4.4 MAXIMUM (AFTERNOON) VENTILATION COEFFICIENT

On the annual frequency patterns (Appendix A.III) the combined effect of the lower frequency 'ridge' of mixing heights less than 200 m and mean wind speeds less than 4.0 m/s results in a net 'ridge' of relatively lower frequencies of ventilation coefficients less than 1000 m^2/s. Thus, compared to the surrounding regions at the same latitude, the Prairies region experiences fewer periods of extremely limited dispersion on an annual basis.

This condition is evident in all seasons except winter. In the latter case, the extension of the lower frequency 'trough' of ventilation coefficients less than 1000 m^2/s from the Mackenzie Valley through central Alberta and across the Prairies reflects the mean position of the stagnating Arctic high pressure ridge. Ventilation coefficients less than 3000 m^2/s occur in over 80% of the non-cold advection cases at this time (Fig. 4.5 a). Moreover, almost 97% of the cases have ventilation coefficients less than 6000 m^2/s (Fig. 4.5 b).

4.5 CONCLUSIONS

From spring to fall, the frequent interchange of widely contrasting airmasses, uniform terrain and interior location make the Prairies region less vulnerable to extended periods of stagnation than many other regions in Canada. In winter, however, the presence of the stagnating Arctic high pressure ridge and direct path for unmodified Arctic air to penetrate across the Prairies make this a critical period from a pollution potential viewpoint.

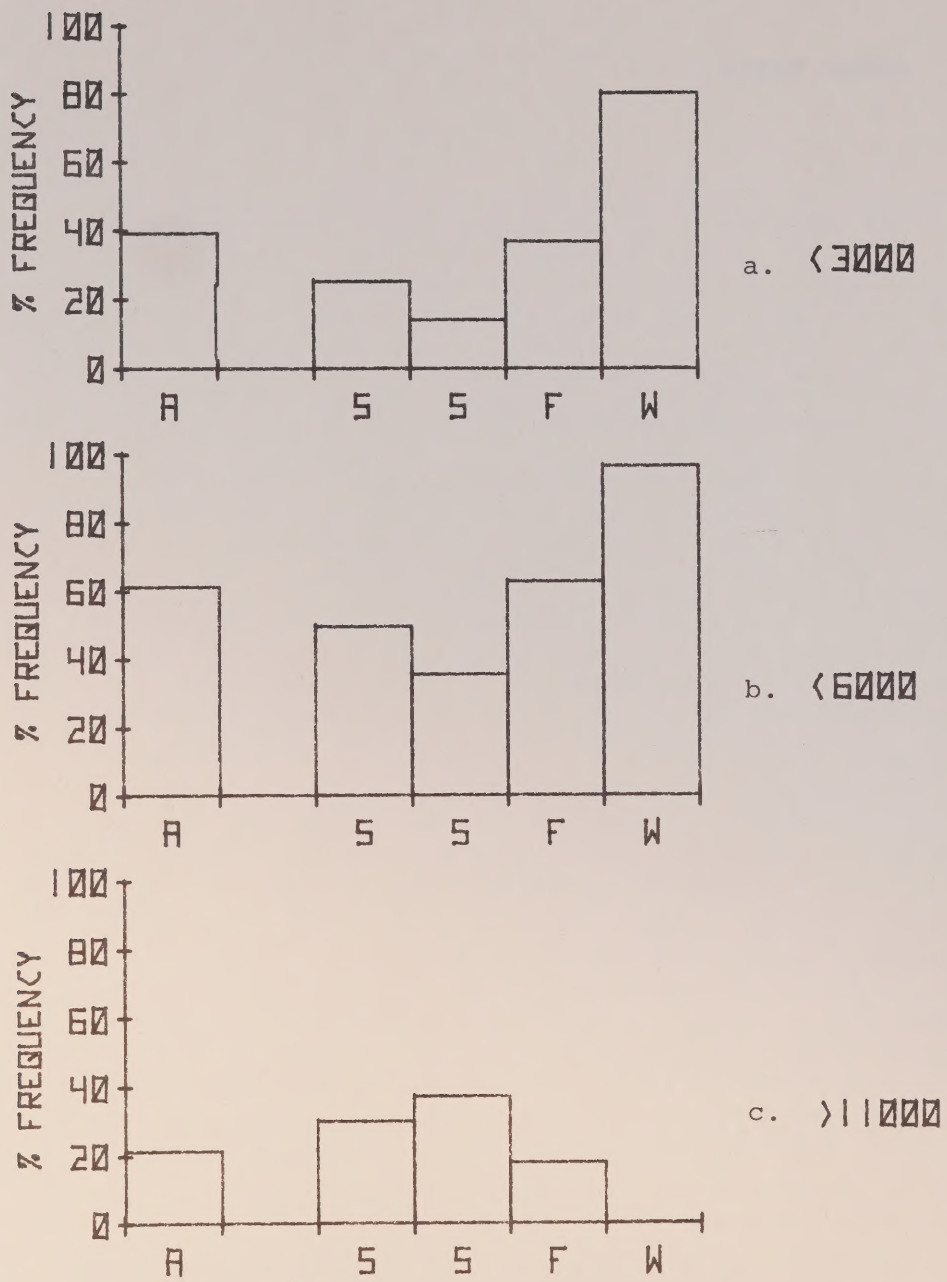


FIG. 4.5 Annual and Seasonal Frequencies of Occurrence of Afternoon Ventilation Coefficients (m^2/s) for the Prairies Region

GREAT LAKES

CHAPTER 5

CHAPTER 5

GREAT LAKES REGION

5.1 INTRODUCTION

The Great Lakes region (Fig. 5.1) is located in the near centre of the North American continent and extends across the most southern latitude belt in Canada. It is also located in a zone of the tropospheric westerlies where maximum sensible heat and latent heat exchange occurs between the tropics and the poles. In spite of the interior location, the Great Lakes have a climate which is described as 'modified continental'. Approximately one-third of the Great Lakes Basin watershed area is lake surface (Phillips, 1969) and Lake Superior which is the largest freshwater lake in the world covers an area over 80,000 square kilometres (Appendix D).

Sixty percent of the land area in the basin surrounding the lakes lies below 30 m ASL. Higher elevations are found along the north shore of Lake Superior and southeast of Lake Huron, and in the Laurentian Highlands to the northeast. In general, the elevation increases inland so that daytime upslope winds occur from spring to early fall (in a lake-breeze) and downslope (clearing) winds occur at night and during the winter (from a land-breeze). A strong northwesterly gradient wind produces weak subsidence over the Niagara escarpment and to the lee of other higher elevations. Deep river valleys (St. Lawrence Lowlands and the Ottawa River Valley) act as preferred pathways for the intrusion of the lake-breeze.

Phillips (1969) noted in the Climatological Summary of the Great Lakes that the combined influence of topography, lake-effect and passage of widely contrasting airmasses make this region more complex than most of similar latitude. This observation may be extended to the mixing depth climatology of the region.

The above physical factors are complicated further by the high population density and major industrial development concentrated in the regions surrounding the lakes, particularly on the U.S. side (e.g., Chicago and Detroit). The consequences of urbanization alter the mesoscale structure of the lower atmosphere around the lakes in the following ways:

i) Atmospheric pollutants reduce the intensity of sunshine by as much as 25% in urban areas (Brown and Chapman, 1968).

ii) Asphalt, concrete, and snow clearing in the winter alter the albedo, reflectivity and thermal efficiency of the underlying surface.

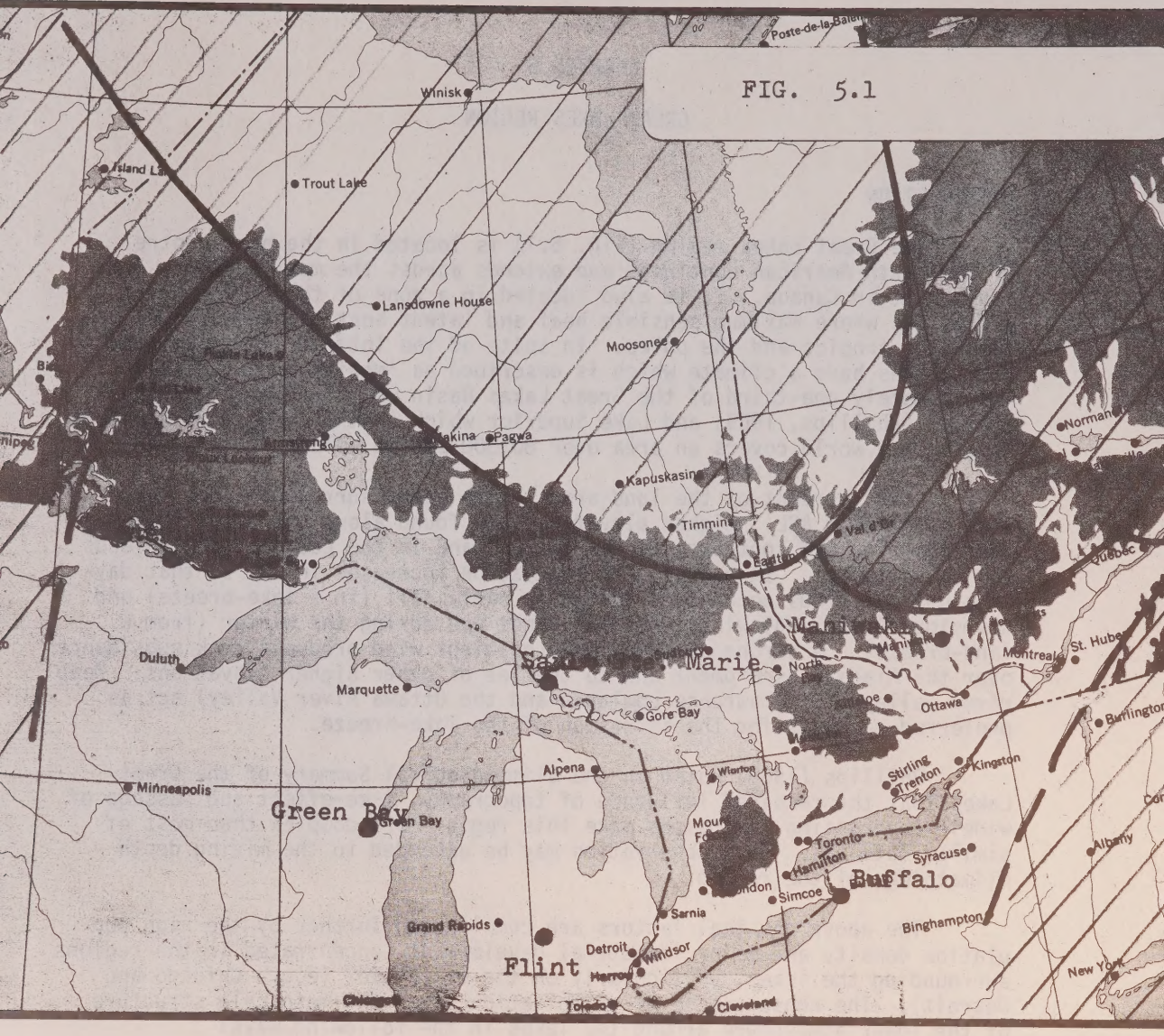
iii) Surface roughness and traffic activity (aircraft, etc.) vary the turbulent mixing characteristics.

iv) Heat generated through industrial and domestic processes contribute to the overall thermal energy available to the area.

(Note: Young (1978) noted that diffusion over cities is enhanced not only due to surface roughness but the great heat capacity of the cities. Net increase in turbulent mixing intensity is about 40% when compared to the open country).

As in the case of the other regions of Canada, the Great Lakes experience considerable variation in mixing depth climatology from site to

FIG. 5.1



GREAT LAKES REGION

● - rawinsonde station sites

site within the region. For example, the following table gives the Mean Seasonal Mixing Depths of rawinsonde stations surrounding the lakes. The data is taken from the Frequency Distributions of Mixing Depth Parameters compiled for rawinsonde stations across Canada (Portelli and Wilson, 1979).

	Spring	Summer	Fall	Winter
Maniwaki	1327	1358	886	583
Buffalo	1135	1386	940	572
Flint	1175	1359	972	697
Green Bay	1248	1372	1017	574
Sault Ste. Marie	1024	1112	769	488
Intl. Falls	1223	1467	898	420

In these cases, the mean can vary by as much as 300 m from one station to another in any particular season.

The above stations (Appendix D) are used to describe the average conditions across the Great Lakes region from season to season. The following sections examine these conditions in terms of relevant controls and compare the results with those of other regions. Caution is advised in using the averaged data with respect to a specific site in the region. Major variations can occur across such a large and diverse region and during the months of a particular season. In cases where on-site upper air data is not available, it is best to use monthly mean data from a nearby rawinsonde station which closely resembles the physical characteristics of the proposed site.

5.2 MAXIMUM (AFTERNOON) MIXING HEIGHTS

5.2.1 General Characteristics

Compared to the other interior continental regions of Canada, the Great Lakes display less seasonal variation in the frequency patterns (Appendix A.I). Nevertheless, variations in the mean of the percentage frequency distribution from season to season is readily apparent in Fig. 5.2. For example, over 65% of the cases in winter have mixing heights less than 600 m while the other seasons average less than 30% (Fig. 5.3 b). For heights above 2000 m seasonal variations are also evident in this modified continental climate. Spring and summer have frequencies around 15% while the fall and winter have negligible values (Fig. 5.3 c).

The moderating influence of the large bodies of water that compose the Great Lakes is largely responsible for the seasonal variations observed in the frequency distributions and patterns. Major water surfaces absorb and store vast amounts of heat during the long summer days and then release this thermal energy in the fall and winter. Because of this heat source and sink effect, areas surrounding the lakes rarely experience extreme hot or cold surface air temperatures or large diurnal fluctuations in these values. Compared to the neighbouring continental regions, the Great Lakes enjoy cooler summers and milder winters, and an extended growing season and frost-free period.

The above modifications in the temperature regimes in areas surrounding the lakes are reflected in the average seasonal mixing height statistics

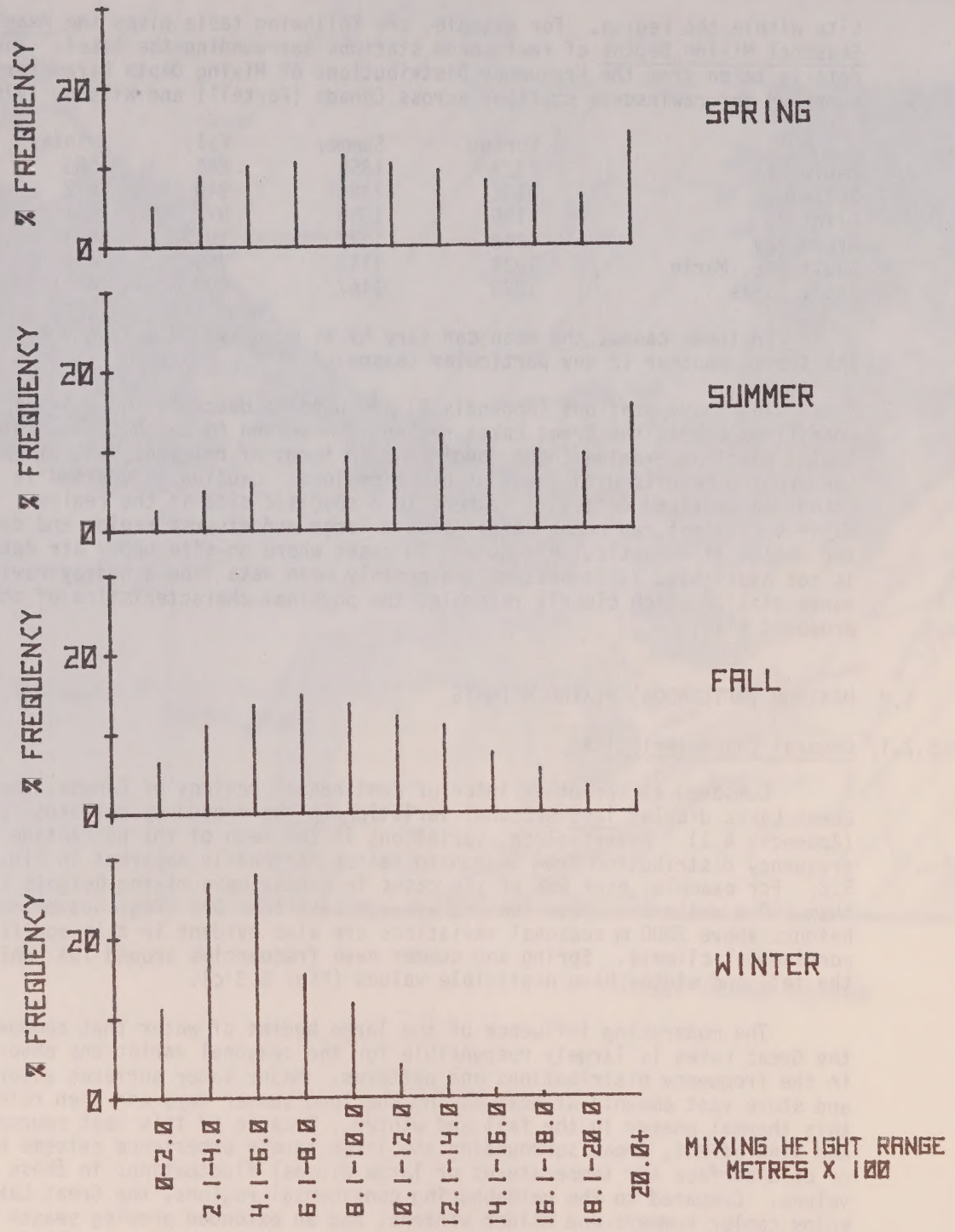


FIG. 5.2 SEASONAL FREQUENCY HISTOGRAMS OF SPECIFIED MAXIMUM MIXING HEIGHTS.

REGION: GREAT LAKES

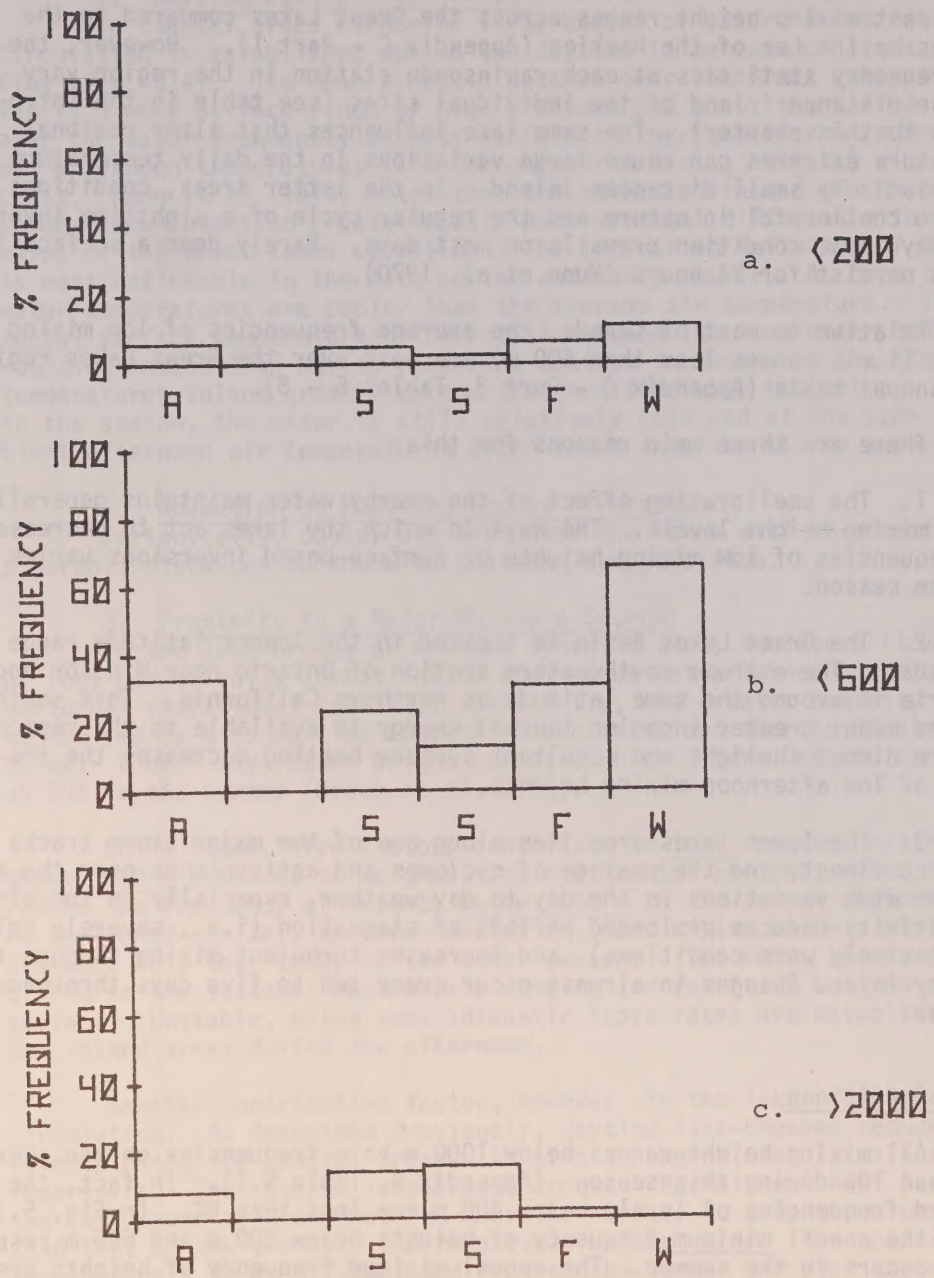


FIG. 5.3 Annual and Seasonal Frequencies of Occurrence of Maximum (Afternoon) Mixing Heights (m) for the Great Lakes Region

across the region. For example, there is less seasonal variation in the significant mixing height ranges across the Great Lakes compared to the Prairies or the Lee of the Rockies (Appendix C - Part I). However, the mean frequency statistics at each rawinsonde station in the region vary with the distance inland of the individual sites (see table in the introduction to this chapter). The same lake influences that alter regional temperature extremes can cause large variations in the daily temperature over relatively small distances inland. In the latter areas, conditions are more continental in nature and the regular cycle of a nighttime inversion and a day lapse condition prevails on most days. Rarely does a surface inversion persist for 24 hours (Munn et al, 1970).

Relative to most of Canada, the average frequencies of low mixing heights (i.e., ranges less than 600 m) are less over the Great Lakes region on an annual basis (Appendix C - Part 2, Tables 5 - 8).

There are three main reasons for this:

1. The ameliorating effect of the nearby water maintains generally higher mixing height levels. The ways in which the lakes act to decrease the frequencies of low mixing heights or surface-based inversions varies with the season.

2. The Great Lakes Basin is located in the lowest latitude range in Canada. The extreme southwestern section of Ontario near Windsor and Lake Erie is around the same latitude as northern California. This southern exposure means greater incoming thermal energy is available to the region. The more direct sunlight and resultant surface heating decreases the frequency of low afternoon mixing heights.

3. The lower lakes area lies along one of the major storm tracks of the continent, and the passage of cyclones and anticyclones over the area produces wide variations in the day to day weather, especially in the winter. This activity reduces prolonged periods of stagnation (i.e., severely cold or excessively warm conditions) and increases turbulent mixing through the boundary layer. Changes in airmass occur every two to five days throughout the year.

5.2.2 Summer Conditions

All mixing height ranges below 1000 m have frequencies on the average less than 10% during this season (Appendix B, Table 5.1). In fact, the combined frequencies of levels below 400 m are less than 8%. In Fig. 5.3 a and b, the annual minimum frequency of heights below 200 m and 600 m respectively occurs in the summer. The annual maximum frequency of heights greater than 2000 m also occurs at this time although it is only in the order of 15% of the occurrences (Fig. 5.3 c).

The greatest frequencies of heights above 1000 m occur in the summer for the Great Lakes region. The combined frequencies of heights in these ranges, however, are much less than the corresponding frequencies in continental regions at similar latitudes (Appendix B, Tables 2.1, 3.1, 4.1 and 5.1). These relatively lower mean mixing heights in the the vicinity of the Great Lakes have the following origins:

1. Daytime Lake-Breeze Effect:

In coastal areas bordering large bodies of water, a net lake-breeze circulation is established during the daytime in periods of light geostrophic flow (Fig. 5.4). The mean synoptic pattern over the Great Lakes in the summer is a weak surface ridge of high pressure and thus, the marine inversion over the water frequently advects inland in the lake-breeze reducing maximum afternoon temperatures (and corresponding mixing heights) along the coast. Munn et al (1970) noted that the advection inland of the spring and summer lake inversion create locally poor vertical diffusion within a few miles of the Great Lakes shoreline. The moderating influence of the lakes is most noticeable in the late spring and early summer. At this time, the water temperatures are cooler than the average air temperature. The horizontal surface temperature differential between the open water and the surrounding heated land masses reaches a maximum in June when the afternoon air temperatures inland greatly exceed that modified over the water. This early in the season, the water is still relatively cold and at the same time, ambient afternoon air temperatures often climb into the mid to upper twenties.

2. Advection of Modified Cooler Airmasses:

Periodically, cooler air from over the lakes will be advected considerable distances inland with a strong synoptic flow.

3. Proximity to a Major Moisture Source:

In the lake-breeze or onshore synoptic flows, moisture (low clouds or fog) periodically advect inland and reduce net afternoon insolation (or nocturnal radiational cooling). Similarily, the greater humidity available to the region aids daytime convective processes and thereby limits the sunshine. Clouds may reduce bright sunshine in shouthern Ontario by as much as 50% in the summer (Brown et al, 1968).

While these three factors contribute to less frequent mixing heights above 1000 m compared to neighbouring continental regions, other factors reduce the frequency of heights below 1000 m to the annual regional minimum. As mentioned earlier, the frequencies of lower mixing heights at this time are much less than those of the other seasons. The main reason for this is of course the seasonal hemispheric warming and resultant heating of the land surface. Unstable, often superadiabatic lapse rates are established over the inland areas during the afternoon.

Another contributing factor, however, is the lake- and land-breeze circulation. As described previously, daytime lake-breezes reduce maximum heights along the coastal areas. At night, however, the lakes act as heat reservoirs. The reverse land-breeze occurs. Radiational heat losses over the land cause air temperatures near the surface to drop to values lower than that of the air over the relatively warmer water. The cooler air over the land sets up an off-the-land flow as the warmer air over the water rises. As a result of these processes, the diurnal surface temperature range along the coast is significantly reduced. In addition, constant turbulent motion is generated through the boundary layer by the closed land- and see-breeze circulations. Early morning inversions are not as intense as those present over large land masses or trapped in deep valleys. Less daytime heating is required to recover from overnight cooling near the lakes and to raise the mixing depths before the modifying lake-breeze is established.

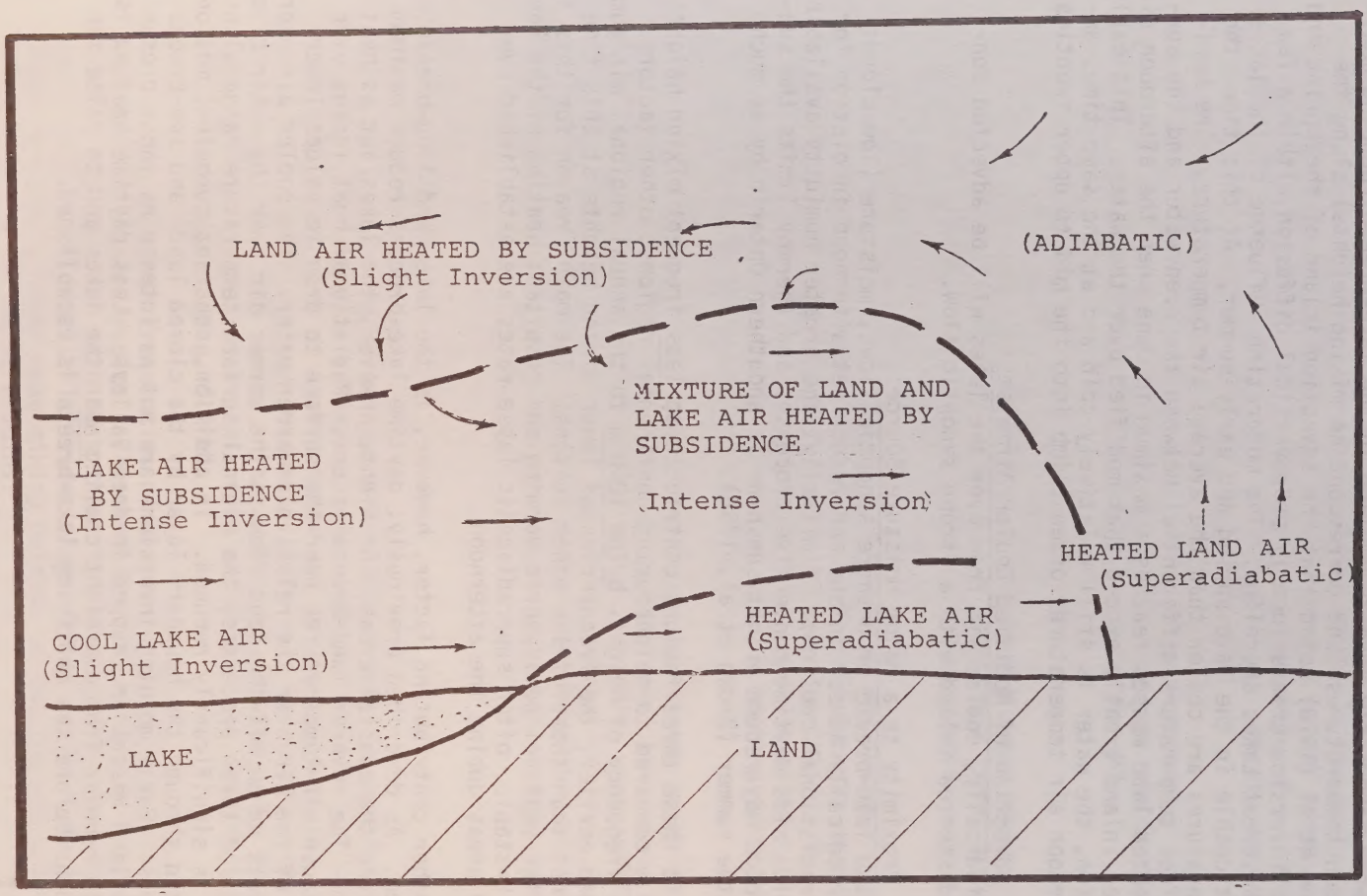


FIG. 5.4 Schematic representation of a lake breeze when the geostrophic wind is light (Munn, 1966) (Copyright: Academic Press, New York)

5.2.3 Winter Conditions

For the Great Lakes region, the greatest annual frequency of mixing heights below 600 m occurs in this season (Fig. 5.3 b). Compared to the other regions, however, the winter frequencies of heights below 200 m and 600 m are the lowest in Canada (Appendix C - Part 2, Tables 4 and 8). The winter frequency distribution in Fig. 5.2 shows that the greatest combined frequencies occur in the 200 m to 600 m ranges. For heights above 1000 m the frequencies drop off rapidly to zero.

During the winter, the large open bodies of water act as heat reservoirs. Land-breezes may occur both in the daytime and at night in the presence of light geostrophic winds. As a result, the air temperature of areas adjacent to the relatively warmer heat and moisture source are moderated a few degrees higher than those of continental areas at similar latitudes and mean minimum temperatures along the lakeshore are much higher than those inland. Similarily, the low level warming of the air immediately over the water in contrast to the colder air at higher levels creates an unstable condition in the boundary layer. The inland extension of this turbulent mixing in the lowest layers varies with the location, proximity to the open water and the mean flow. The shore of Lake Ontario, for example, rarely freezes in the winter. The regional southerly winds will advect warmer air off the water without actually generating a closed lake-breeze circulation (Munn et al, 1969).

During the winter, a southerly flow across the region and warm advection are commonly associated with an advancing low pressure system from the west or southwest. A continuous succession of cyclonic storms sweep over the Great Lakes from fall to spring and bring relatively warm, moist air from the south alternating with cold air outbreaks from the north. These storms move in from the prairies or up the Mississippi Valley and periodically stall and intensify over the lakes. The resultant strong circulation causes the inland advection of convectively unstable air from over the lakes to areas in the 'lee' of the flow.

During the winter months, however, the mean surface and upper flows over the Great Lakes have a strong northwesterly component. Aloft, the major trough position retrogresses from the east to a position over the lakes by January. As a result, winter precipitation is heaviest to the lee of Lake Huron and Georgian Bay, and lightest further inland to the lee of the Uplands (Brown et al, 1968). Areas to the lee of the lakes receive the major portion of their total snowfall from these 'lake-effect snowstorms'. The cold winds crossing the comparatively warm lakes are a major factor in contributing to the lee snowfalls. Well-known snowbelts of the Great Lakes region are generally to the south and east of each lake (Phillips, 1969).

Although the unstable 'lake effect' and associated turbulent mixing maintain relatively lower frequencies of mixing heights below 600 m, the highest combined frequencies in the region still remain confined below 1000 m. Several factors contribute to these low mixing height values during this season. The first is the seasonally reduced insolation. This incoming solar radiation is further reduced by the presence of cloud. (December is the dullest month of the year in the Great Lakes area. Clouds may reduce bright sunshine by as much as 75% across southern Ontario (Brown et al, 1968).

Periods of bright sunshine usually occur deep in the cold air behind a cold front. Strong subsidence in the following high pressure system maintains generally clear skies. However, diurnal modification of the surface temperature is limited due to the cold and highly reflective snow cover. (The highest values of the reflective coefficient (80% or more) occurs for fresh snow compared to less than 20% for a snow-free surface). In these cases, surface- or near surface-based inversions will persist over the snow surface for long periods of time. (Note: Around cities and other major industrial or developed areas, the dust, pollutants and snow clearing modify the reflective coefficient and thus the amount of solar radiation reaching the surface. Also, the overall heat generated in these areas maintains locally neutral to unstable lapse conditions.)

5.2.4 Spring and Fall Conditions

The seasonal frequency distribution of mixing heights (Fig. 5.2) indicates that spring and fall conditions are similar with respect to heights below 2000 m. For example, frequencies of mixing heights below 600 m (Fig. 5.3 b) are close to 30% in both transition seasons. The major difference occurs for heights greater than 2000 m (Fig. 5.3 c). The frequencies in this category in the spring are much greater than that in the fall.

In the fall, warm quasistationary anticyclones and accompanying subsidence inversions linger over the lakes and frequently shroud coastal areas in haze (Munn et al, 1970). Evaporation from the lakes is greatest in the fall and early winter when the water surface temperatures are relatively warmer than the air temperatures. (Annual evaporation is greatest from Lake Erie, the warmest and shallowest of the lakes, and least from Lake Superior). Weak onshore flows in the afternoon will advect coastal fog and stratus inland and thereby reduce maximum temperatures and mixing heights. In the spring, when the lake temperatures are cold relative to that of the air, evaporation is least. However, the coastal fog and humidity present in the fall reduce overnight radiational losses and weaken morning inversions near the lakes. In these areas, minimum temperatures average 4 to 5 degrees (Celcius) higher in October than in April (Phillips, 1969). Although the radiation inversions are less pronounced in the fall along the coast, the additional energy required to 'burnoff' the fog and raise the afternoon mixing heights may contribute to the lower frequency of heights above 2000 m at this time.

Other typical features of the region which contribute to the lower frequency of heights above 2000 m compared to the spring include the valley effect. A frontal inversion above the St. Lawrence and Ottawa river valleys occur mainly in the fall and winter. At this time, cold air is trapped in these valleys while warmer air passes aloft. This synoptic situation may produce a high pollution potential sometimes after only a few hours (Munn et al, 1970).

The cooling influence of the lakes is best defined in the late spring and early summer when daytime temperatures at stations surrounding the lakes are 4 to 5 degrees Celsius cooler than at stations a few miles inland. Yet, the average frequencies of mixing heights above 2000 m are the annual highest (near 20%) in both seasons (Fig. 5.3 c). This suggests that mixing heights

reach higher values (compared to other seasons) before the onset of the lake-breeze.

Rawinsonde stations within the region such as Green Bay, Sault Ste. Marie and Buffalo would best characterize this effect. A cursory examination of the mean mixing height values (Portelli, 1977) at the stations closest to the lakes indicates that the heights on the average are higher in spring than fall.

5.3 MEAN TRANSPORT WIND SPEEDS THROUGH THE MIXED LAYER

5.3.1 General Frequency Characteristics

In all seasons except summer, calm to light mean mixed layer winds across the region are usually less frequent than those of the surrounding Canadian land masses (Appendix C - Part 2, Tables 13 - 16). For the region, mixing layer winds less than 4.0 m/s are most frequent in the winter (over 25% of the cases) and almost half as frequent in the spring (Fig. 5.5 a). Spring also has the highest frequency of mean mixed layer winds greater than 12.0 m/s (Fig. 5.5 b).

From Table 5.2 (Appendix B) the annual percentage frequency distribution shows that almost 70% of the cases are concentrated in the 4.1 to 12.0 m/s range. Winds stronger than 16.0 m/s occur less than 2% of the time in any season. Also, on the calm to light wind annual frequency pattern (Appendix A.II) the Great Lakes as well as the Prairies region are in a relative minimum frequency 'ridge'. As in the case of the Prairie grasslands this pattern may be related to the fairly uniform surface of the Great Lakes and surrounding basin. As noted earlier, 60% of the land area in the basin lies below 30 m ASL (Phillips, 1969). Shaw et al (1972) noted that flat areas such as the southern Prairies and large bodies of water seldom experience light surface winds.

5.3.2 Spring Conditions

During the spring, the contrast in airmasses is great and the frequency of intense rapidly moving synoptic systems the highest of the year. Constant interaction takes place between the Arctic, Maritime and Polar airmasses (and sometimes Tropical trowals) at this southern latitude. The stronger circulations ensure a relatively high mean speed through the mixing layer and often breakdown existing inversions. Anticyclones and associated light winds are not persistent.

5.3.3 Summer Conditions

This season has the smallest frequency of mixing layer winds greater than 12.0 m/s (Fig. 5.5 b). Weak circulations and ill-defined synoptic systems dominate the summertime pattern across the region. A more stably stratified layer is present over the open waters and shoreline since the air over the water is modified by the relatively colder underlying surface. The major source of stronger winds at this time would be cold frontal passages and

gustiness associated with daytime convection. Instability generated over the heated land surrounding the lakes, and the diurnal lake- and land-breeze circulations maintain almost continual motion in the boundary layer at this time. Amost 75% of the cases have mean winds in the 4.1 to 8.0 m/s range (Appendix B, Table 5.2). Calm to light mean winds occur more often than in the spring, but less frequently than in the winter (Fig. 5.5 a).

5.3.4 Fall Conditions

The frequency of mean winds less than 4.0 m/s is about the same as that in the summer. The stronger winds, however, increase in frequency over that of summer (Fig. 5.5 a and b).

Better defined cyclones replace the weak summer systems. Cold air injected from the northwest increases in frequency and feeds further development. Periodically, however, light winds develop in high pressure ridges that build behind the systems. During the period of 'Indian Summer', these anticyclones drift slowly over the eastern part of the continent, producing calm, hazy days and cool nights.

5.3.5 Winter Conditions

Frontal cyclone activity continues through the winter maintaining measurable frequencies of mean winds greater than 12.0 m/s. However, the anticyclones that follow in the cold air and the reflective snow cover now over much of the region maintain a higher frequency of surface-based or low level inversions, and a corresponding higher frequency of calm to light winds compared to the other seasons (Fig. 5.5 a).

Compared to the other regions, however, the Great Lakes have relatively lower frequencies of calm to light mean winds through the mixing layer, with the exception of the Atlantic and Appalachian regions (Appendix C - Part 2, Table 16). As described earlier, the Great Lakes act as heat reservoirs and maintain an unstable lapse rate in the lowest layers above the water surface. Similarily, the modifying heat island effect of heavily industrialized areas and large population centres surrounding the lakes maintains greater mixing in the lowest 1000 m above the surface. The moderating effect of the above processes on the surrounding areas reduces the intensity and frequency of surface-based inversions and associated light winds. In addition, winter cyclones will periodically stall and deepen over the Great Lakes, and further contribute to the general circulation of the lower atmosphere.

5.4 MAXIMUM (AFTERNOON) VENTILATION COEFFICIENTS

The spring and summer frequencies of ventilation coefficients less than 3000 m^2/s and 6000 m^2/s (Fig. 5.6 a and b, respectively) are almost identical and the lowest of the year. Similarily, the frequencies of coefficients greater than 11,000 m^2/s (Fig. 5.6 c) are the highest of the year in both seasons. In the winter, on the other hand, over 50% of the cases have ventilation coefficients less than 3000 m^2/s (Fig. 5.6 a), and over 80% are less than 6000 m^2/s (Fig. 5.6 b).

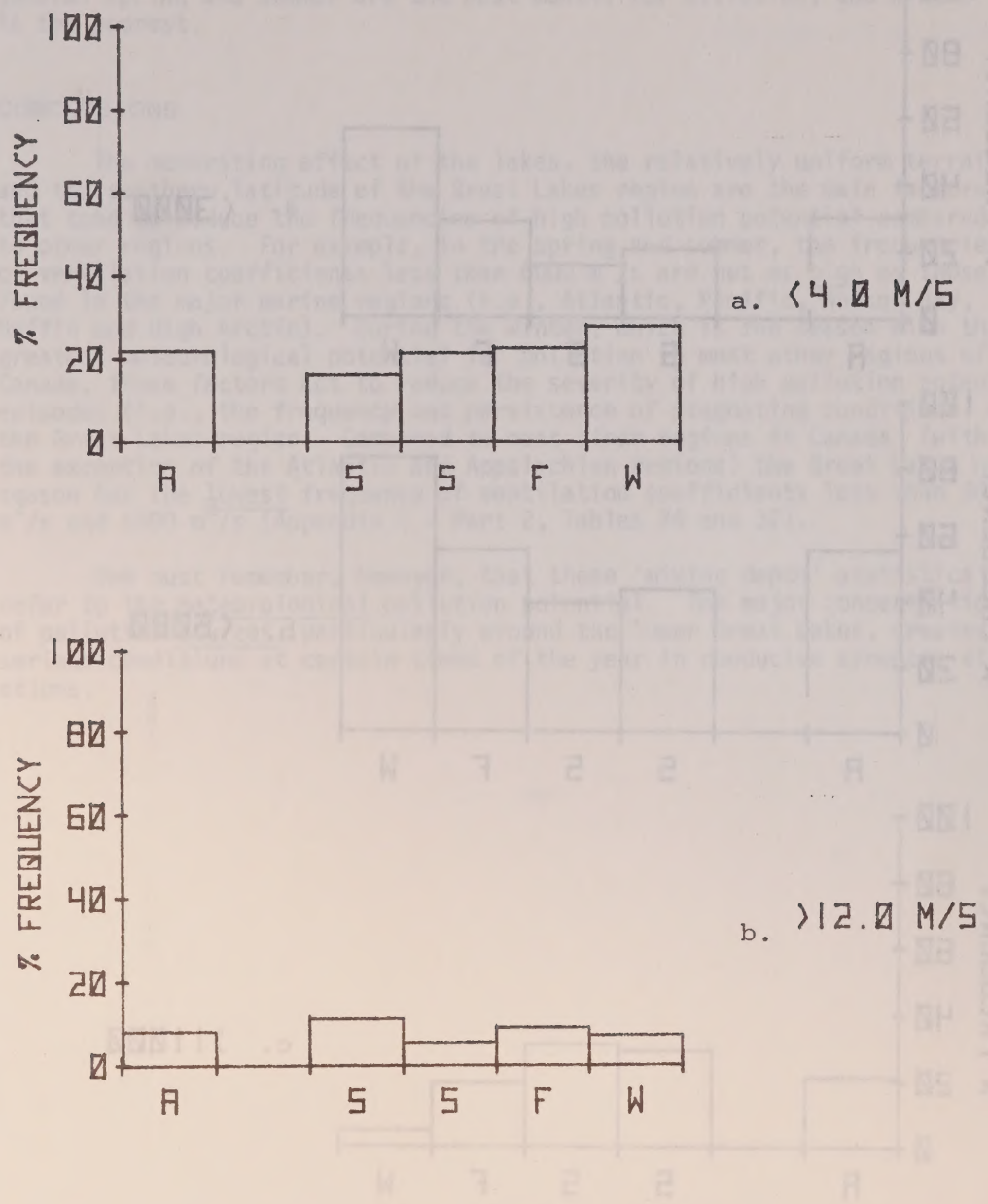


FIG. 5.5 Annual and Seasonal Frequencies of Occurrence of Mean Wind Speeds Through the Mixing Layer (m/s) for the Great Lakes Region

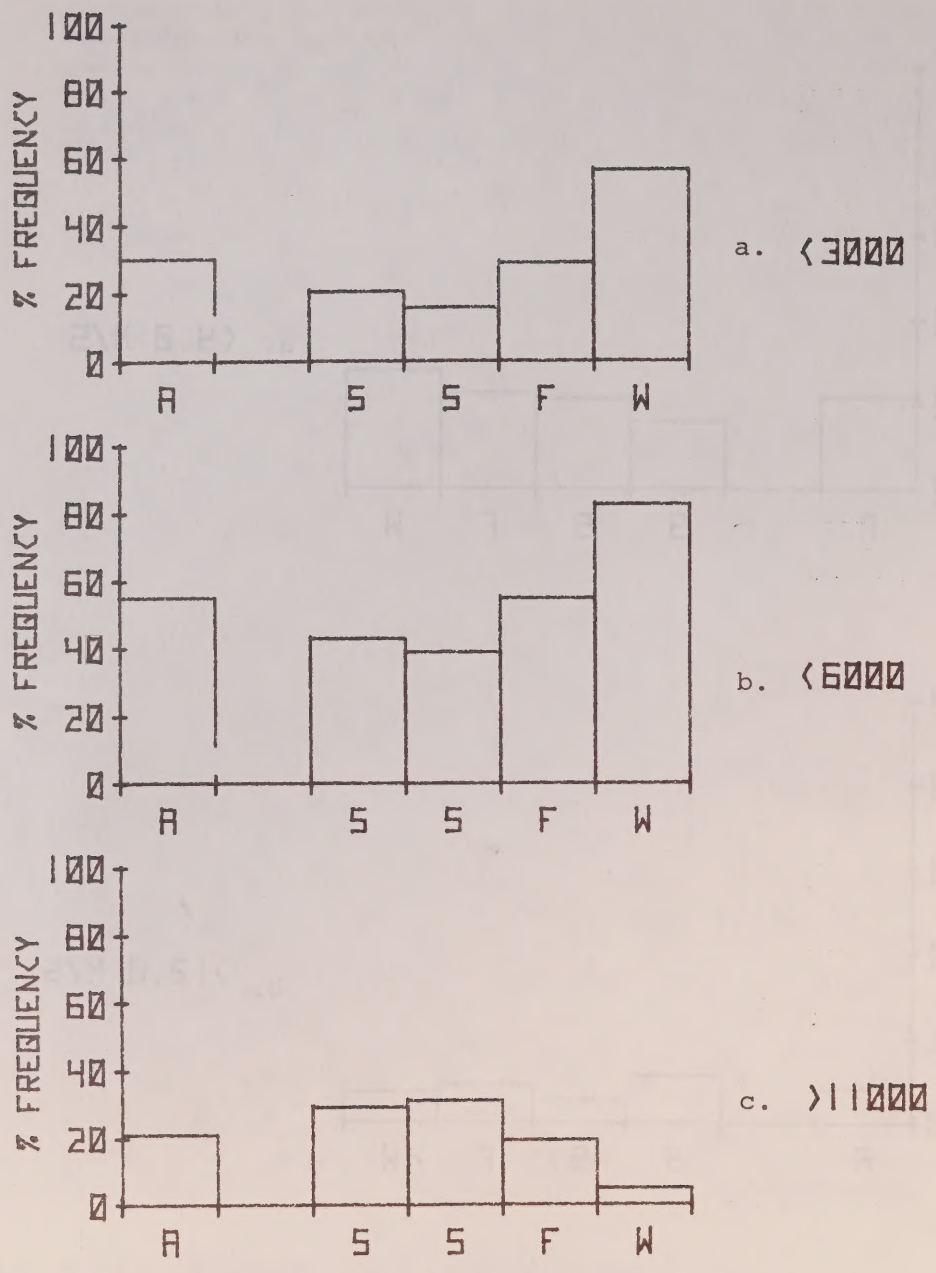


FIG. 5.6 Annual and Seasonal Frequencies of Occurrence of Afternoon Ventilation Coefficients (m^2/s) for the Great Lakes Region

These seasonal frequency averages over the region suggest that in general spring and summer are the best months for diffusion, and winter is the poorest.

5.5 CONCLUSIONS

The moderating effect of the lakes, the relatively uniform terrain and the southern latitude of the Great Lakes region are the main factors that tend to reduce the frequencies of high pollution potential compared to other regions. For example, in the spring and summer, the frequencies of ventilation coefficients less than 6000 m^2/s are not as high as those found in the major marine regions (i.e., Atlantic, Pacific, Hudson Bay, Baffin and High Arctic). During the winter, which is the season with the greatest meteorological potential for pollution in most other regions of Canada, these factors act to reduce the severity of high pollution potential episodes (i.e., the frequency and persistence of stagnating conditions) over the Great Lakes region. Compared to most other regions in Canada (with the exception of the Atlantic and Appalachian regions) the Great Lakes winter season has the lowest frequency of ventilation coefficients less than 3000 m^2/s and 6000 m^2/s (Appendix C - Part 2, Tables 24 and 32).

One must remember, however, that these 'mixing depth' statistics refer to the meteorological pollution potential. The major concentration of pollution sources, particularly around the lower Great Lakes, creates serious conditions at certain times of the year in conducive synoptic situations.

EASTERN CORDILLERA

CHAPTER 6

CHAPTER 6

APPALACHIAN REGION (EASTERN CORDILLERA)

6.1 INTRODUCTION

The Appalachian region extends from the Vermont border through parts of the Quebec province south of the St. Lawrence River to the Gaspé Peninsula, and includes the northwestern section of New Brunswick (Fig. 6.1). This narrow region is located along the Atlantic Ocean side of the continent and runs essentially parallel to the coastline. Deep valleys and long narrow lakes run parallel to the ridges along a northeast-southwest orientation. The highest tops of the ranges that make up the Appalachian chain average around 1400 metres. (A larger area with similar physical characteristics is found further south and has been identified as a separate 'atmospheric area' in the U.S. Air Pollution Climatology. See Appendix F). Large variations occur in the topography throughout the region. For example, the southeast portion of the Great Lakes basin ascends from about 75 m along Lake Ontario to nearly 800 m in the Adirondak Mountains of New York State - an increase of about 540 m in 100 km horizontal distance. As a result of the variable terrain, upper-air data in the boundary layer over the region is very site-dependent. This is similar to but not as extreme as the situation in the Rockies region described in Chapter 2. The mountains and highlands of the Eastern Cordillera are much lower than those of the Western Cordillera. Furthermore, since they are located on the east side of the continent in the westerlies zone, their effect on the climate is relatively slight.

Nevertheless, on the frequency analyses of various mixing depth ranges, variations from the surrounding regions are evident in the patterns. Other analyses of the mixing depth parameters give similar results. For example, relatively higher mean mixing heights (Portelli, 1977) occur in all seasons along this region compared to the Atlantic region to the east, and to the Great Lakes region to the west. Similarily, mean afternoon mixing height patterns analyzed through the U.S. (Holzworth, 1972) indicate relatively higher mean values occur along the Appalachian chain.

There are two northern U.S. rawinsonde stations located along the Eastern Cordillera and available in the study. Albany N.Y. (el. 84 m) is located in a valley between the Adirondack Mountains (tops 1000 to 1600 m) to the west, the Catskill Mountains to the south and the Green Mountains (tops 1400 to 1600 m) through Vermont to the east. Caribou (el. 189 m) is located in northern Maine, near the border of northern New Brunswick.

6.2 MAXIMUM (AFTERNOON) MIXING HEIGHTS

6.2.1 General Characteristics

Like their Western Cordillera counterparts, radiosonde stations in the Appalachian region show considerable seasonal variation in their mixing depths (Fig. 6.2). The differences between the seasons, however, are not as extreme along the east coast. For example, the frequency of mixing heights less than 600 m (Fig. 6.3 b) is over 50% in the winter in contrast to less

(EASTERN CORDILLERA)

● - rawinsonde station sites

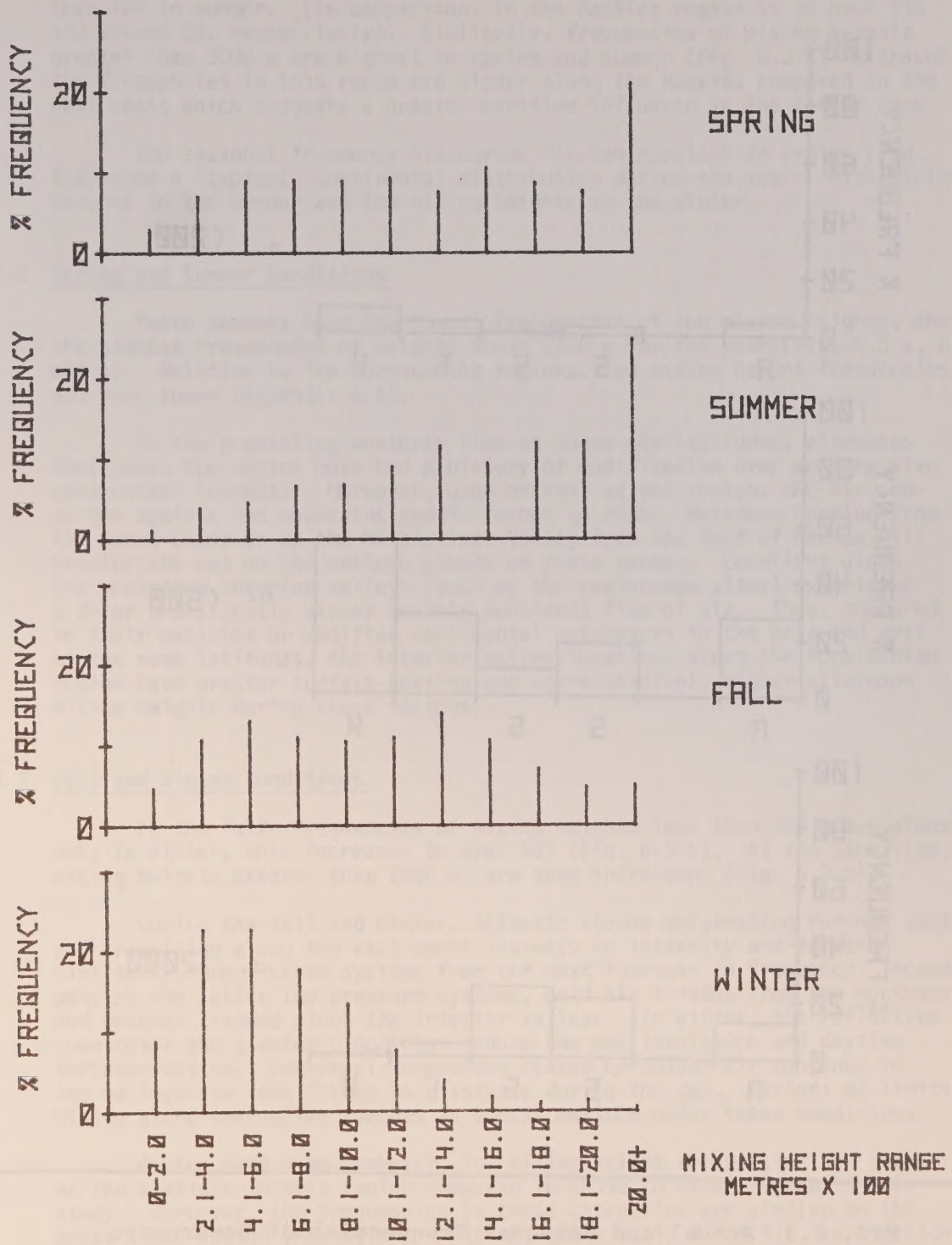


FIG. 6.2 SEASONAL FREQUENCY HISTOGRAMS OF SPECIFIED MAXIMUM MIXING HEIGHTS

REGION: APPALACHIANS

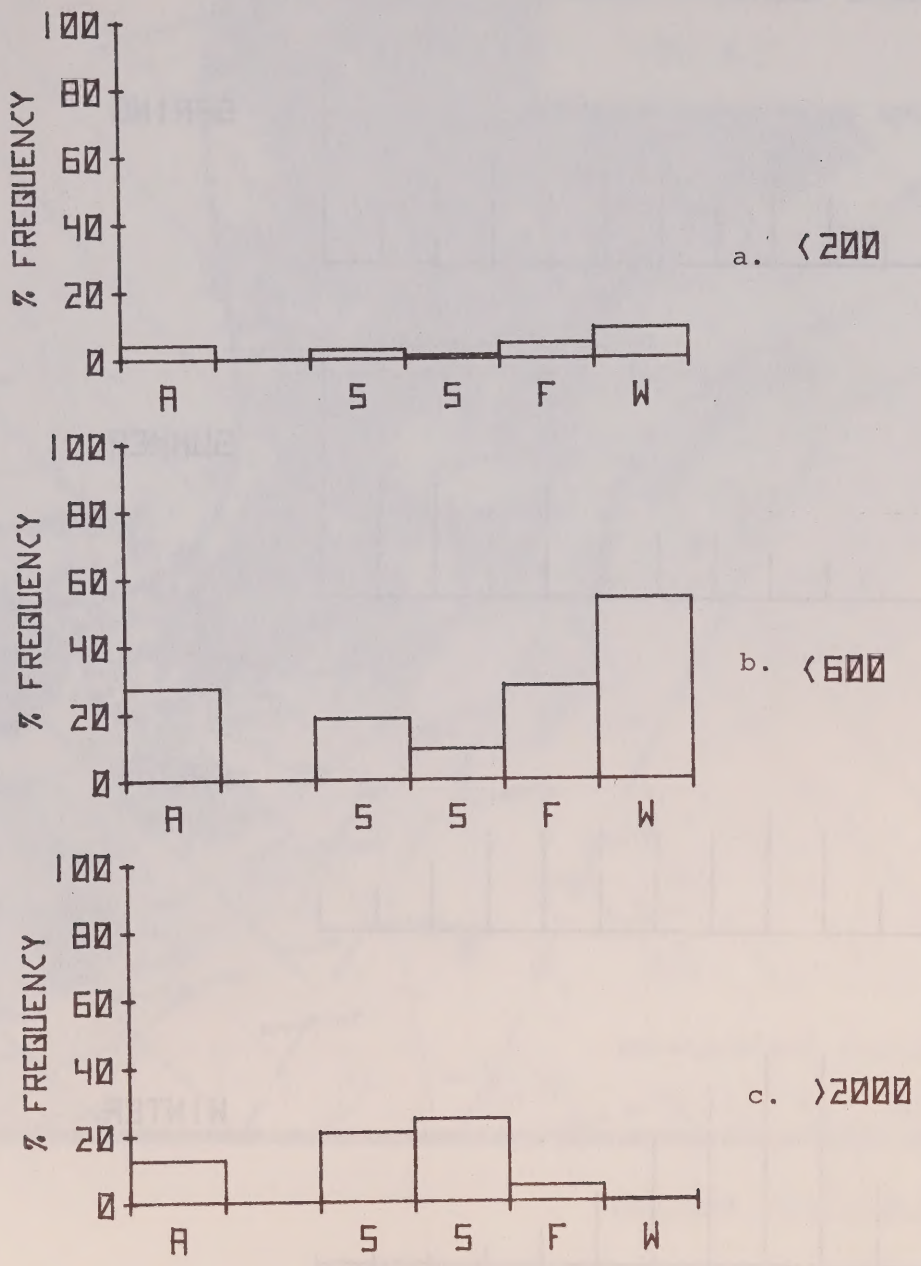


FIG. 6.3 Annual and Seasonal Frequencies of Occurrence of Maximum (Afternoon) Mixing Heights (m) for the Appalachian Region

than 10% in summer. (In comparison, in the Rockies region it is over 85% and around 5%, respectively). Similarily, frequencies of mixing heights greater than 2000 m are highest in spring and summer (Fig. 6.3 c) although the frequencies in this range are higher along the Rockies compared to the east coast which suggests a greater maritime influence in the latter case.

The seasonal frequency histograms for the Appalachian region (Fig. 4.2) show a 'typical' continental distribution during the year: high mixing heights in the summer and low mixing heights in the winter.

6.2.2 Spring and Summer Conditions

These seasons have the lowest frequencies of low mixing heights, and the highest frequencies of heights above 2000 m for the year (Fig. 6.3 a, b and c). Relative to the surrounding regions, low mixing height frequencies are much lower (Appendix A.I).

In the prevailing westerly flow at these mid-latitudes, airmasses that cross the region have had a history of modification over an extensive continental landmass. Moreover, upon arrival at the region, the air converges against the mountains and is forced to rise. Moisture carried from the Great Lakes or up the Mississippi Valley from the Gulf of Mexico will precipitate out on the western slopes of these ranges. Locations along the protected interior valleys (such as the rawinsonde sites) experience a drier and slightly warmer (weakly subsided) flow of air. Thus, compared to their maritime or modified continental neighbours to the east and west at the same latitudes, the interior valley locations along the Appalachian region have greater surface-heating and correspondingly higher afternoon mixing heights during these seasons.

6.2.3 Fall and Winter Conditions

In the fall, frequencies of mixing heights less than 600 m are almost 30%; in winter, this increases to over 50% (Fig. 6.3 b). At the same time, mixing heights greater than 2000 m are very infrequent (Fig. 6.3 c).

During the fall and winter, Atlantic storms originating further south and travelling along the east coast increase in intensity and duration. Similarily, Great Lakes systems from the west increase in frequency. Accompanying the latter low pressure systems, cold air invades from the northwest and becomes trapped along the interior valleys. In winter, the reflective snow cover and greater cloudiness reduce the net insolation and daytime surface-heating. Low-level inversions caused by colder air confined in the valleys are less likely to dissipate during the day. Periods of limited mixing along the valley reaches an annual maximum under these conditions.

At the same time, however, low mixing height frequencies are lowest at the stations in this region compared to those in other regions in the study. Moreover, the frequencies in these categories are similar to the Great Lakes region (Appendix C - Part 2, Table 3, 4, 8 and 9). In addition to the southern latitude of the region, other factors reduce the relative frequencies of low mixing heights and periods of stagnation in these areas. First of all, very cold airmasses are modified by the time they reach this eastern region. Similarily, modification by the relatively milder

Atlantic airmasses reduce the intensity of deep surface-based inversions throughout the region. And finally, a weak subsiding flow protects inner valley locations from the harsh Arctic outbreaks from the northwest.

6.3 MEAN TRANSPORT WIND SPEEDS THROUGH THE MIXED-LAYER

There is little seasonal variation demonstrated in Fig. 6.4 a and b. Mean mixed-layer winds less than 4.0 m/s have the highest frequency in winter and the lowest in spring, although all frequencies are only around 20%. Stronger mixed-layer winds greater than 12.0 m/s have the highest frequency in spring.

For reasons described earlier, low mixing heights and surface-based inversions occur with greater frequency in winter. Correspondingly less horizontal diffusion occurs through the stable layer near the surface. However, compared to other regions in Canada, the frequencies of calm to light mixed-layer winds are among the lowest in all seasons. The Appalachian and Great Lakes regions again have similar frequencies in this category (Appendix C - Part 2, Tables 13 - 16). In fall and winter, this relative reduction in limited horizontal mixing may be attributed to the number of synoptic systems crossing these regions, the lower frequencies of stagnating cold high pressure ridges, and the modification of colder airmasses. Stronger winds occur in spring when surface-heating and afternoon mixing heights are greater, and more intense and faster moving systems occur.

6.4 MAXIMUM (AFTERNOON) VENTILATION COEFFICIENTS

The seasonal variation evident in the mixing height frequency distribution is reflected by the ventilation coefficients. Frequencies of ventilation coefficients less than 3000 m^2/s and 6000 m^2/s (Fig. 6.5 a and b, respectively) are highest in winter and lowest in summer. Similarily, frequencies of ventilation coefficients greater than 11,000 m^2/s (Fig. 6.5 c) are highest in spring and summer and lowest in winter.

Relative to the other regions of Canada, the Appalachian region has among the lowest frequencies of limited diffusion conditions throughout the year (Appendix C - Part 2, Tables 21 - 24).

6.5 CONCLUSIONS

The location of this region along: (i) the southern latitude belt in Canada, (ii) the Eastern Cordillera in a prevailing westerly flow over the continent, and (iii) the major storm track route, allows greater low-level diffusion and airmass exchange throughout the year.

The inner valley locations are protected from stagnating maritime influences in the spring and summer, and polar influences in the fall and winter.

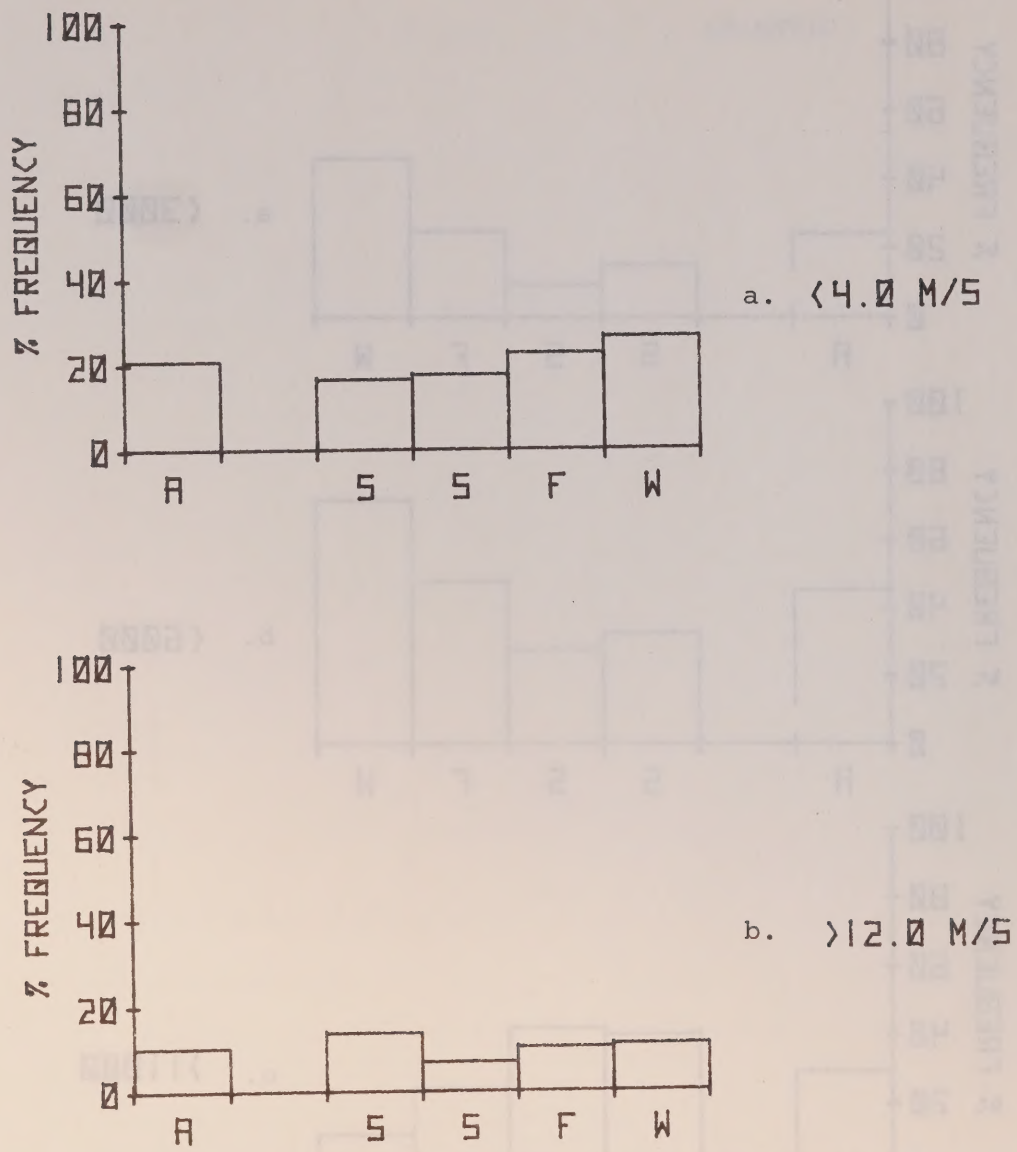


FIG. 6.4 Annual and Seasonal Frequencies of Occurrence of Mean Wind Speeds Through the Mixing Layer (m/s) for the Appalachian Region

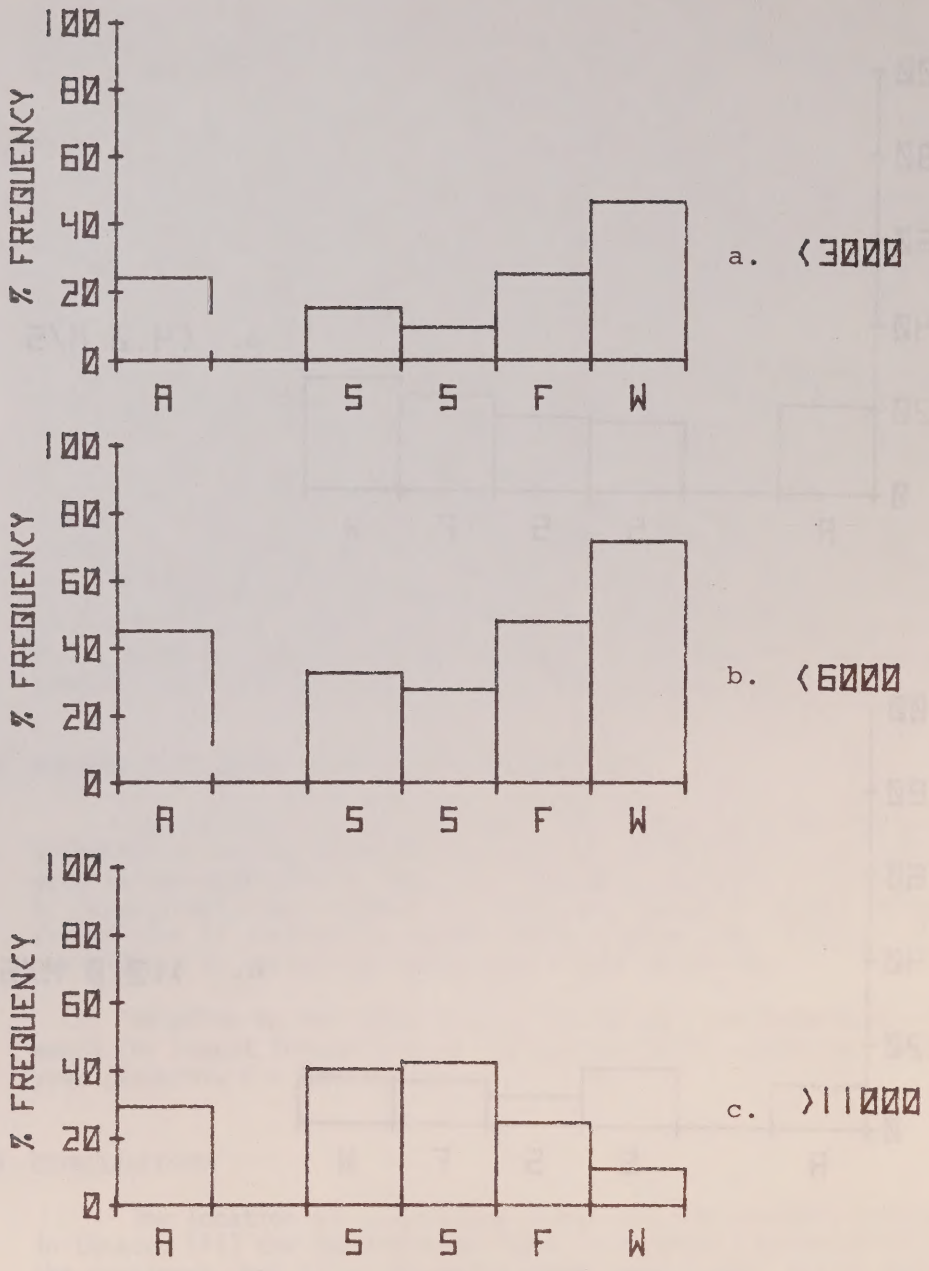
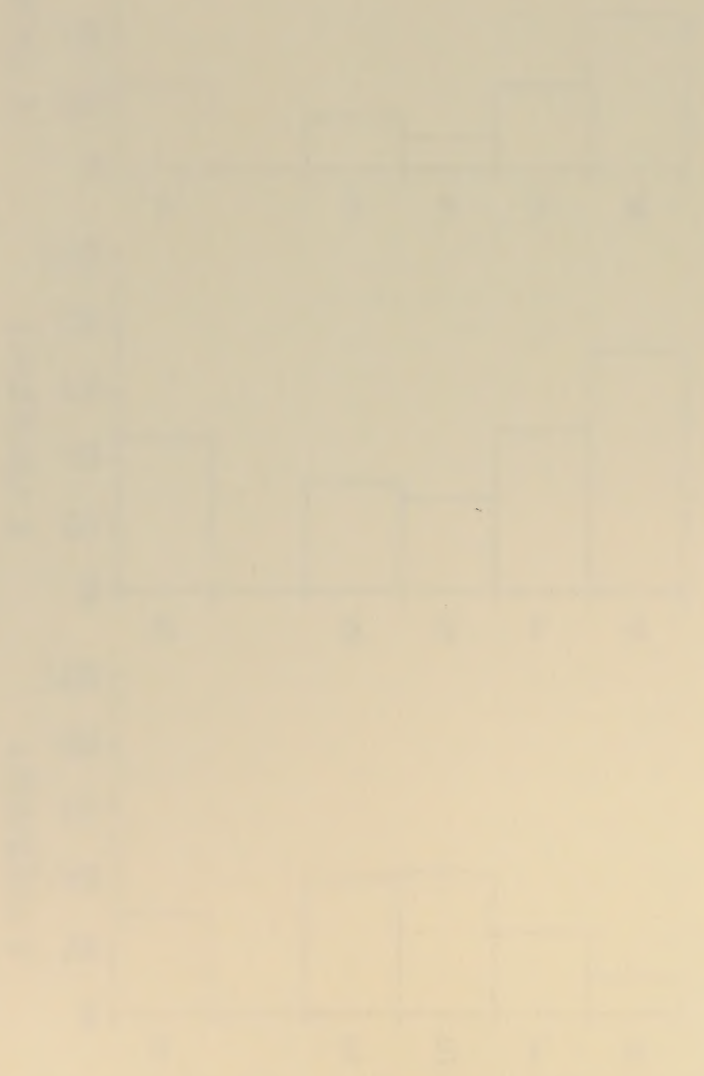


FIG. 6.5 Annual and Seasonal Frequencies of Occurrence of Afternoon Ventilation Coefficients (m^2/s) for the Appalachians Region

ATLANTIC

CHAPTER 7



CHAPTER 7

ATLANTIC REGION

7.1 INTRODUCTION

The Atlantic Region (Fig. 7.1) borders on the vast Atlantic Ocean. The presence of the large body of salt water to the east of the coastal region modifies the regional mixing depth climate considerably. The year-round open waters and incoming tides, the cold and warm ocean currents, and the often violent Atlantic winter storms all contribute to variations in the thermal structure of the planetary boundary layer, and the seasonal diffusion characteristics along the coast.

Although the land rises towards the Appalachian Highlands, Laurentian Shield and rocky outcrops on Newfoundland, the effects of these relatively lower ranges on the Atlantic coastal conditions are not as pronounced as those along the Pacific coastline. These mountain systems are located along the eastern border of an immense continental landmass, and in combination with a mean westerly flow aloft, provide a more typically continental rather than maritime climate to the east coast provinces. (For example, the mean annual range of temperatures is about twice as great on Nova Scotia coast as on the west coast of Vancouver Island).

Representative stations selected include Sept Isles, Stephenville, Argentia and Sable Island (Appendix D). All of these rawinsonde sites are less than 60 m ASL and within visible distance of the Atlantic Ocean or Gulf of St. Lawrence. Interior locations at higher elevations along the coast, therefore, are not adequately represented in the boundary layer by the upper-air data available. Caution is advised when interpolating data between topographically different sites within the region.

7.2 MAXIMUM (AFTERNOON) MIXING HEIGHTS

7.2.1 General Characteristics

A notable characteristic of the afternoon mixing height frequency distribution for this region (Fig. 7.2) is the little variation between seasons. For example, the frequencies of heights below 600 m (Fig. 7.3 b) and above 2000 m (Fig. 7.3 c), change very little from season to season. In all seasons, the greatest frequencies occur for mixing heights below 1000 m, and virtually negligible values occur for those above 2000 m (Appendix B, Table 7.1). The frequencies of mixing heights below 200 m and 600 m (Fig. 7.3 a and b, respectively) are a maximum in the summer. The Atlantic region ranks second only to the High Arctic as the region with the highest frequency of low mixing heights during this season (Appendix C - Part 2, Tables 2 and 6).

On the frequency patterns of ranges below 600 m (Appendix A.I) a 'trough' of relatively higher frequencies extends from the Atlantic Ocean into the Gulf of St. Lawrence in all seasons except the winter. The contrast in frequencies between maritime and inland locations appears to be the greatest in the spring.

● - rawinsonde station sites

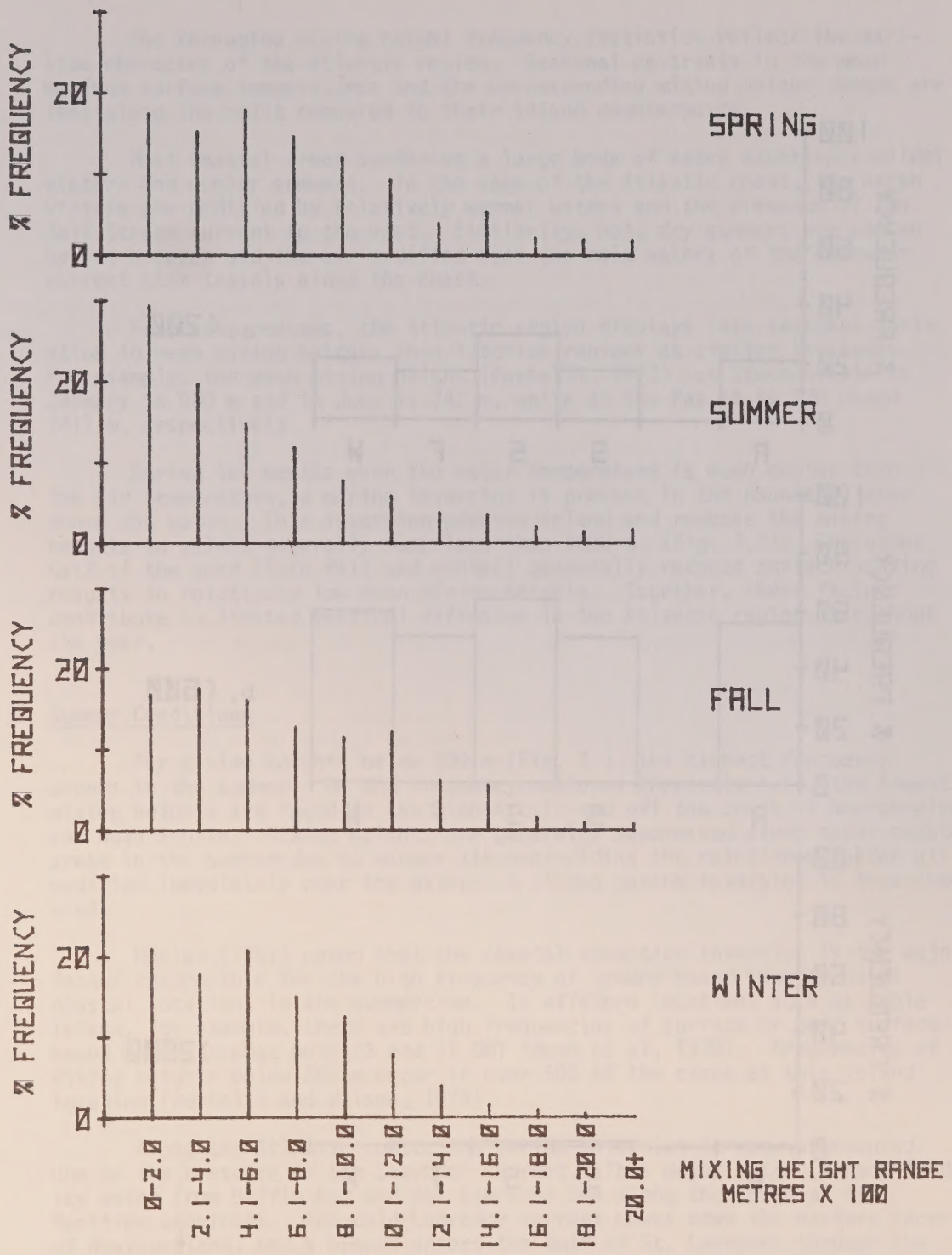


FIG. 7.2 SEASONAL FREQUENCY HISTOGRAMS OF SPECIFIED MAXIMUM MIXING HEIGHTS.
REGION : ATLANTIC

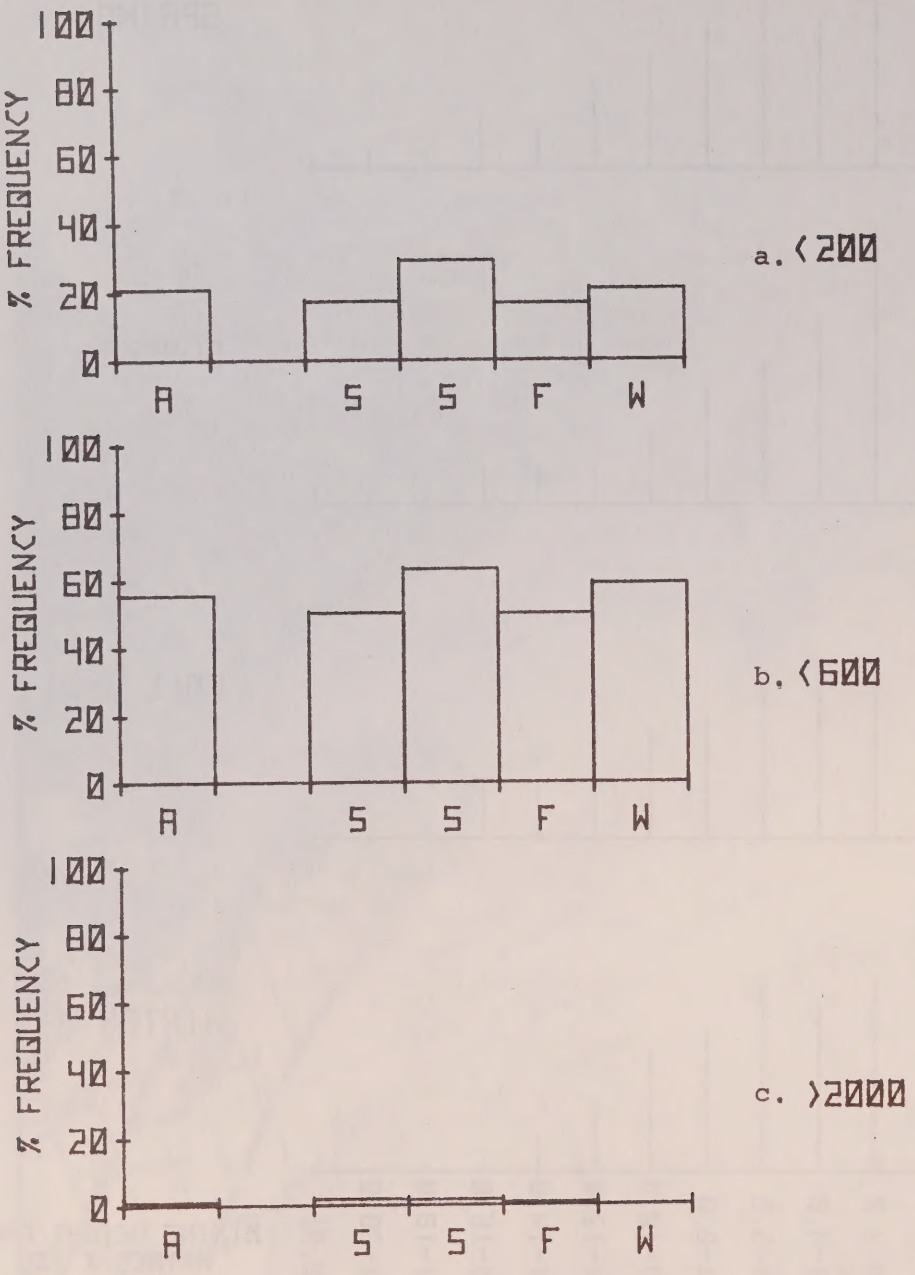


FIG. 7.3 Annual and Seasonal Frequencies of Occurrence of Maximum (Afternoon) Mixing Heights (m) for the Atlantic Region

The foregoing mixing height frequency statistics reflect the maritime character of the Atlantic region. Seasonal contrasts in the mean maximum surface temperatures and the corresponding mixing height ranges are less along the coast compared to their inland counterparts.

Most coastal areas bordering a large body of water experience milder winters and cooler summers. In the case of the Atlantic coast, the harsh winters are modified by relatively warmer waters and the presence of the Gulf Stream current to the east. Similarily, hot, dry summers are cooled by sea-breezes and the air modified over the cold waters of the Labrador current that travels along the coast.

For these reasons, the Atlantic region displays less seasonal variation in mean mixing heights than interior regions at similar latitudes. For example, the mean mixing height (Portelli, 1977) at Stephenville in January is 580 m and in June is 742 m, while at The Pas it is 238 m and 1411 m, respectively.

During the months when the water temperature is much cooler than the air temperature, a marine inversion is present in the boundary layer above the water. This inversion advects inland and reduces the mixing heights to values generally much less than 1000 m (Fig. 7.2). The other half of the year (late fall and winter) seasonally reduced surface heating results in relatively low mean mixing heights. Together, these factors contribute to limited vertical diffusion in the Atlantic region throughout the year.

7.2.2 Summer Conditions

For mixing heights below 200 m (Fig. 7), the highest frequency occurs in the summer. On the frequency patterns (Appendix A.I), the lowest mixing heights are found in the High Arctic and off the coast of Newfoundland and Nova Scotia. Mixing heights are generally suppressed along major coastal areas in the summer due to warmer air over-riding the relatively colder air modified immediately over the water. A strong marine inversion is thus created.

Hosler (1961) noted that the coastal advection inversion is the major factor responsible for the high frequency of ground-based inversions at coastal locations in the summertime. In offshore locations such as Sable Island, for example, there are high frequencies of surface or near surface-based inversions at both 23 and 11 GMT (Munn et al, 1970). Frequencies of mixing heights below 200 m occur in over 50% of the cases at this island location (Portelli and Wilson, 1979).

Along the Atlantic coast, the marine inversion is very pronounced due to the presence of the Labrador current. This major ocean current feeds icy water from Baffin Bay and the Labrador Sea along the coast of the Maritime provinces. The cold Labrador current moves down the eastern shore of Newfoundland, and a branch enters the Gulf of St. Lawrence through the Strait of Belle Isle. This strong Arctic component is felt as far south as the St. Lawrence estuary (Wilson, 1973).

July is the warmest month of the year in most sections of the maritime provinces. Stratus and fog frequently form as warm, moist air cools

and condenses in the stably stratified layer above the cold waters. The periods of fog at sea and along the coast peak in the late spring and early summer months. Along the Atlantic Coast of Nova Scotia and in the Bay of Fundy, the greatest frequency of fog occurs in July (The Climate of Canada, 1967). Sea-breezes advect the marine stratum inland, reducing the net incoming solar radiation and inhibiting maximum surface temperatures along the coast. Summer afternoon temperatures are not as high in these regions as those in southern Ontario at the same latitude. Correspondingly, lower frequencies of mixing heights above 1000 m occur at this time (Appendix B, Table 7.1).

From the end of the spring to early fall, the mean synoptic pattern that dominates along the east coast is a warm, quasistationary anticyclone. Periods of high pollution potential occur when the weak westerly gradient surface winds and subsidence inversion associated with the Bermuda high pressure area produce stagnating conditions.

7.2.3 Spring and Fall Conditions

The frequency distribution of mixing height ranges is similar for both seasons and shows a slight improvement over the summer conditions (Fig. 7.2). Although the highest frequencies are still concentrated in the lowest 1200 m, there is more normal distribution below this level. During the transition seasons, the combined frequencies of mixing heights above 1000 m are the highest of the year (Appendix B, Table 7.1).

The maximum period for storm activity along the east coast takes place from fall to spring. Many of these systems intensify in the coastal waters. The principal area of cyclogensis extends from Cape Hatteras to the waters around Newfoundland (Bursey, 1977). This activity results in more frequent airmass exchange and maintains greater low level mixing throughout the period compared to summer. However, compared to interior continental or modified continental regions in the spring, the frequencies of low mixing heights are much greater along the Atlantic coast as shown below in Tables 1 and 5 (taken from Appendix C - Part 2).

TABLE 1: Less than 200 m

Spring

1.	High Arctic	55.2%
2.	Hudson Bay	18.7
3.	Baffin	17.3
4.	Atlantic	17.3
5.	Mackenzie Valley	9.7
6.	Prairies	5.4
7.	Lee Rockies	5.2
8.	Great Lakes	4.9
9.	Pacific	4.1
10.	Central Quebec	3.2
11.	Rockies	2.9
12.	Appalachians	2.8

TABLE 5: Less than 600 m

Spring

1.	High Arctic	93.2%
2.	Baffin	70.3
3.	Hudson Bay	68.4
4.	Atlantic	50.2
5.	Mackenzie Valley	42.4
6.	Prairies	31.7
7.	Quebec	25.2
8.	Pacific	25.2
9.	Lee Rockies	23.6
10.	Great Lakes	23.6
11.	Appalachians	18.6
12.	Rockies	13.5

Warm, southerly air sweeps over the cold waters of the Labrador current at this time, forming a very stable layer above the water surface. Resultant surface-based advection inversions and fog banks can persist for weeks in coastal areas (Barrie, 1978).

7.2.4 Winter Conditions

During the winter season, low mixing heights less than 600 m are more frequent than those during the transition seasons, but slightly less frequent than those in the summer (Fig. 7.3 b). Compared to most other regions of Canada at this time, however, mixing heights in this category occur least often (Appendix B - Part 2, Table 8). This is a consequence of the moderating influence of the relatively milder Atlantic waters (and Gulf Stream current). These warmer waters maintain an unstable lapse rate in the lowest levels of the atmosphere above the ocean surface.

Cold, polar air entering from the northwest has a previous history of passage over an immense continental landmass. (The Hudson Bay and Gulf of St. Lawrence act as almost continuous snow-covered landscape). When the cold, dry airmasses interface the warm, moist air modified over the water, unstable convective cloud streets develop in the mean northwesterly offshore flow. Preceeding the invasion of cold air, low pressure systems pass along southern coastal sections of the region and into the waters off the east coast of Newfoundland. Influxes of moist Atlantic air in these cyclonic flows carry the instability inland. In addition to thermal instability these storms provide greater mechanical mixing.

7.3 MEAN TRANSPORT WIND SPEEDS THROUGH THE MIXING LAYER

7.3.1 General Characteristics

In most seasons, stronger mean wind speeds (i.e. greater than 12.0 m/s) occur more often at the Atlantic rawinsonde sites than at those in any other region of Canada (Appendix C - Part 2, Tables 17 - 20). Winter has the highest frequency of mean speeds in this range. (This is almost double the winter frequency of that of any other region in Canada.) At the same time, the annual frequency pattern of mean winds less than 4.0 m/s shows a relative minimum area along the Atlantic coast (Appendix A.I).

7.3.2 Summer Conditions

Calm to light mean transport wind speeds reach an annual maximum frequency during the summer. At the same time, mean wind speeds greater than 12.0 m/s are an annual minimum (Fig. 7.4).

The marine inversion and lack of well-defined synoptic gradients are responsible for the limited horizontal mixing that occurs. (The lowest mean monthly surface wind speeds are recorded in July. For example, light surface winds and surface calms occur 84% of the time at Yarmouth in July, and 40% at P.E.I. in the same months, compared to 50% and 34% respectively in January.)

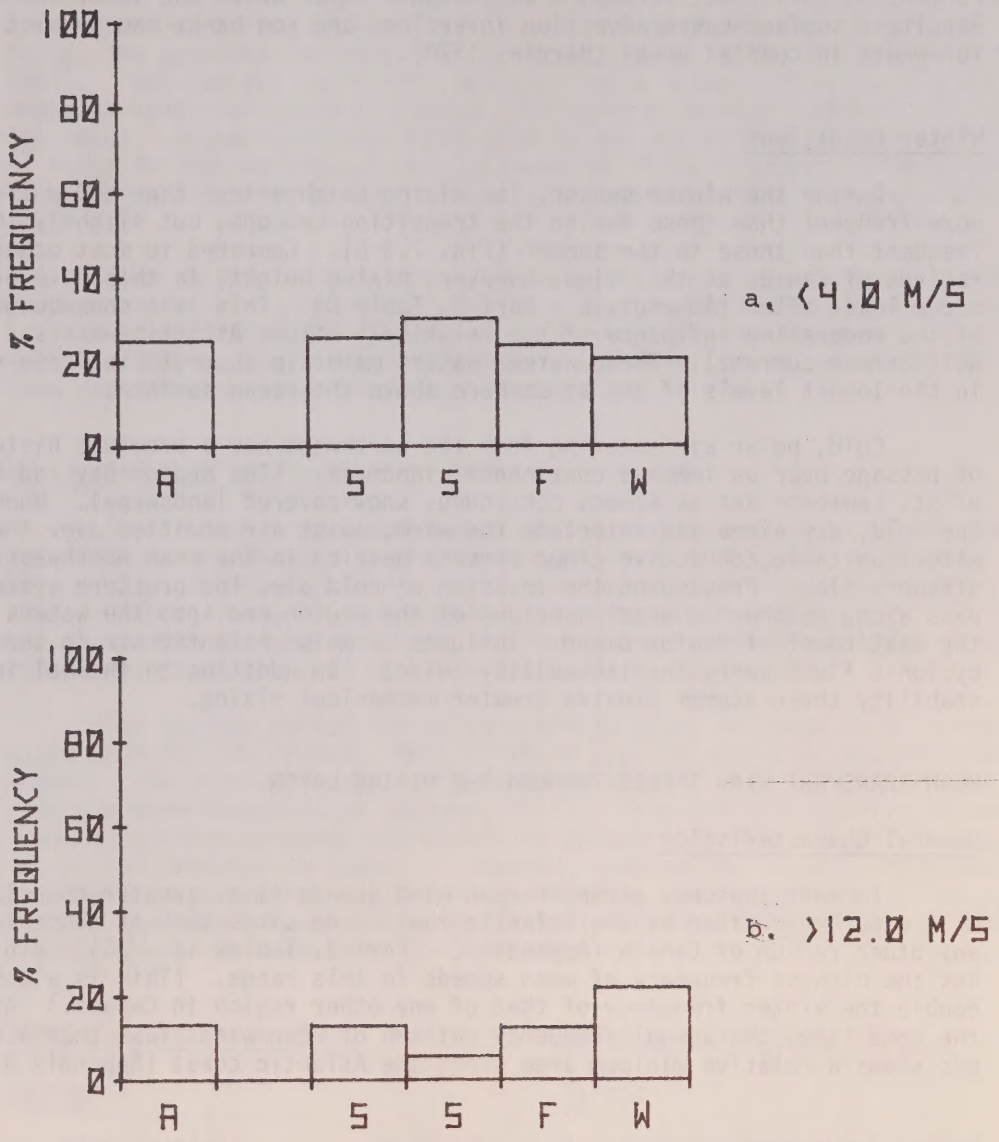


FIG. 7.4 Annual and Seasonal Frequencies of Occurrence of Mean Wind Speeds Through the Mixing Layer (m/s) for the Atlantic Region

7.3.3 Winter Conditions

The highest frequency of mean transport wind speeds through the mixed layer greater than 12.0 m/s occurs at this time.

As mentioned earlier, the principal area of cyclogensis from fall to spring extends from Cape Hatteras to the waters around Newfoundland. Many of these systems intensify in the unstable air over the Atlantic waters and produce gale to storm force winds (Bursey, 1977). Cyclonic development and stronger sustained gradient winds occur due to i) thermal instability in the boundary layer, ii) lack of significant frictionally retarding features (over the water), and iii) the cold air injections from the continental regions interfacing the relatively warm maritime airmasses. (Average surface winds are strongest in the coldest months of winter because of the high frequency of stormy weather. Light surface winds and calms occur with corresponding low frequencies.)

7.4 MAXIMUM (AFTERNOON) VENTILATION COEFFICIENTS

Although the horizontal ventilation is generally good, the vertical mixing is severely inhibited throughout the year. The greatest mixing height frequencies occur below 1000 m in all seasons. These limited mixing heights result in a high frequency of ventilation coefficients less than 3000 m^2/s and 6000 m^2/s in the summer, and relatively high frequency in the same ranges in the winter in spite of the stronger mean wind speeds (Fig. 7.5 a and b, respectively).

7.5 CONCLUSIONS

The high frequencies of limited mixing conditions throughout the year make this region one of high pollution potential. These conditions are of particular concern during the spring thaw and summer growing season when the impact of pollutants would have their greatest detrimental effect. (In the summer, the Atlantic and Pacific regions have over 80% of the cases less than 6000 m^2/s (Appendix C - Part 2, Table 22).

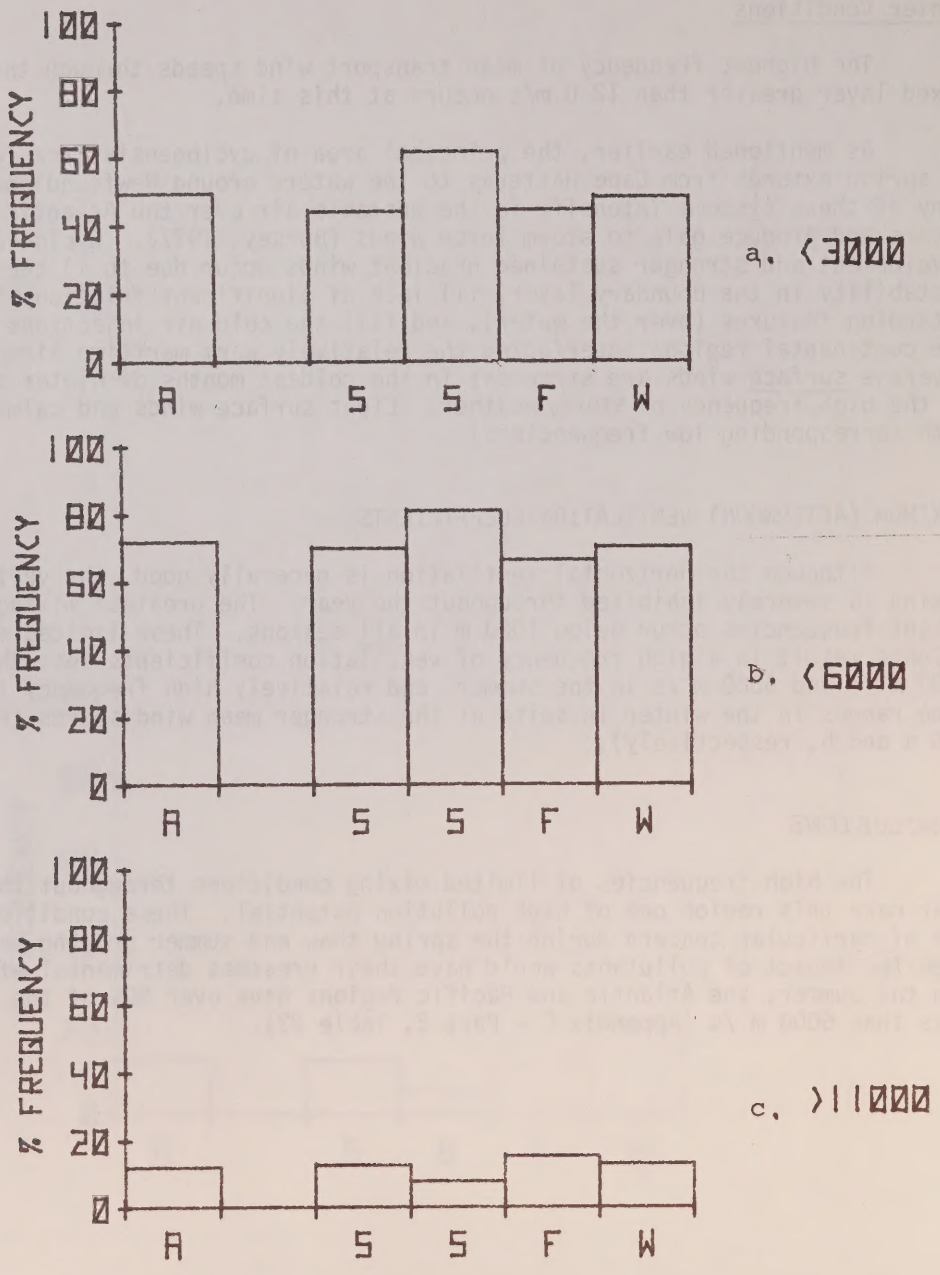


FIG. 7.5 Annual and Seasonal Frequencies of Occurrence of Afternoon Ventilation Coefficients for the Atlantic Region

LAURENTIAN PLATEAU

CHAPTER 8

CHAPTER 8

CENTRAL QUEBEC-LABRADOR REGION

(Laurentian Plateau)

INTRODUCTION

This region covers a broad continental area of the Laurentian Plateau (part of the Canadian Shield) extending from the rugged highlands north of the St. Lawrence River to south of the Hudson Strait. It is bounded on the west by the Hudson Bay and in the east by the Labrador Sea (Fig. 8.1). The monotony of the plateau country is reflected in the frequent rounded summits and numerous shallow lake-filled hollows. Only across northern Labrador and the extreme southern Laurentian Highlands does the land rise abruptly. Vast evergreen (coniferous) forest covers most of the region. (Conifers are especially adapted to cold snowy winter climates. In addition, they can withstand summer droughts that occur in this elevated continental climate). The entire region has areas of permanently frozen sub-soil. The northern boundary more or less marks the southern limit of widespread permafrost.

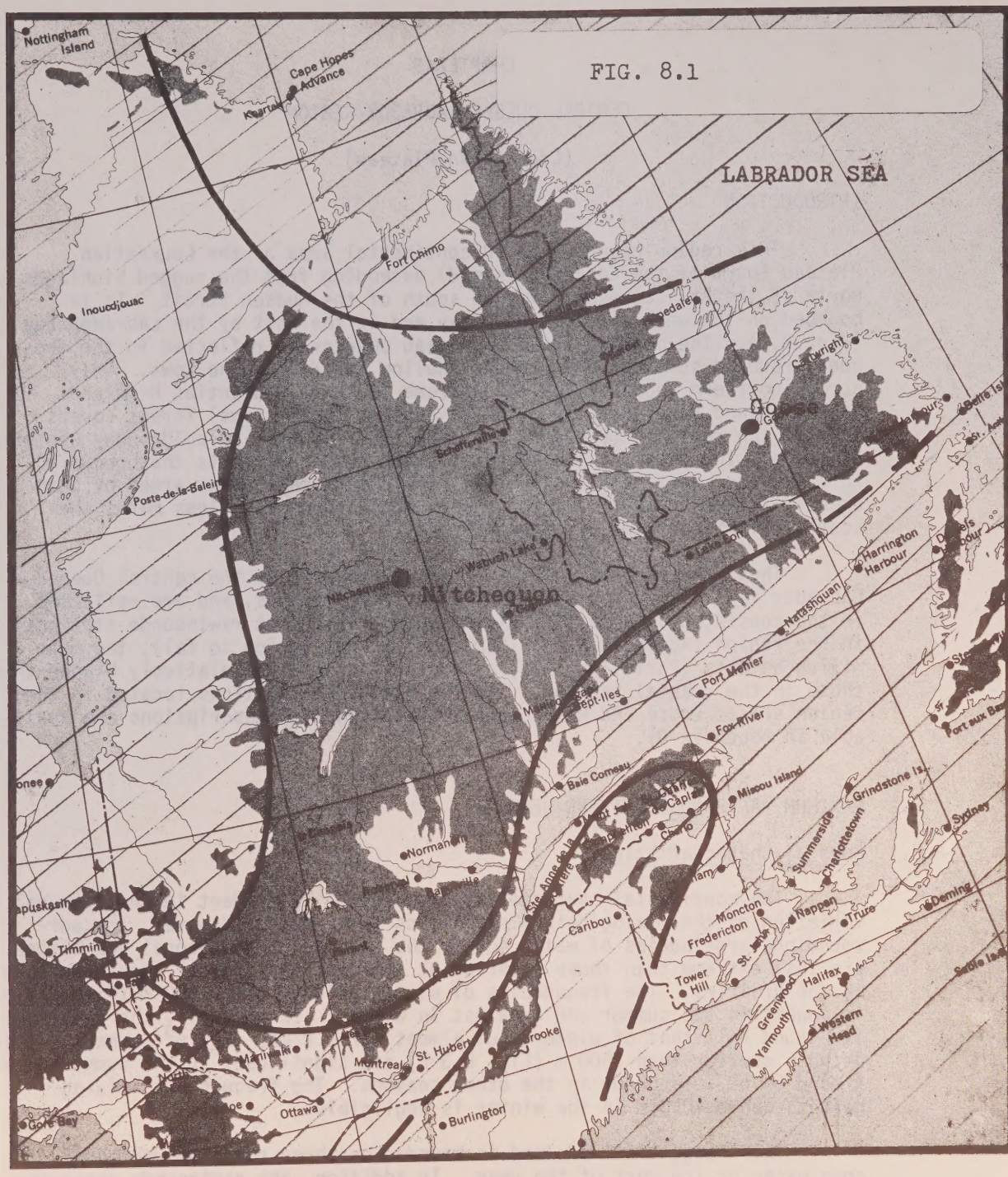
These physiographical characteristics separate the central Quebec-Labrador region from the surrounding maritime regions, and are reflected in the consistently different mixing height values at rawinsonde stations in the region (Appendix A.I). Similarily, from spring to fall, the mean mixing heights (Portelli, 1977) at these stations are relatively higher than those in the coastal regions. The two rawinsonde stations located in the region are at Goose and Nitchequon. (Detailed site descriptions are available in Appendix D).

8.2 MAXIMUM (AFTERNOON) MIXING HEIGHTS

8.2.1 General Characteristics

The continental character of this region is evident in the seasonal variation of the mixing height statistics (Fig. 8.2). However, the surrounding large bodies of water modify the climate, and seasonal variations are less extreme than those observed at interior continental locations such as the Prairies. The frequencies of mixing heights below 600 m (Fig. 8.3 b) is lowest in the summer and greatest in winter. In the fall, the frequency is around half that of winter, but almost three times that of summer. Mixing heights greater than 2000 m (Fig. 8.3 c) are significant in the summer only. Around 5% or less occur in the other seasons. The frequency of mixing heights above 1000 m in the winter is negligible.

This large tract of land is bounded on three sides by very cold open water or ice most of the year. In addition, the radiosonde observing sites have large lakes nearby. The proximity to cold moisture sources tends to modify the basic continental nature of the region. Yet, compared to the Great Lakes region, central Quebec is more continental than maritime in character. Low mixing heights occur more frequently in fall and winter, and high mixing heights occur more frequently in the summer.



CENTRAL QUEBEC - LABRADOR REGION

(LAURENTIAN PLATEAU)

● - rawinsonde station sites

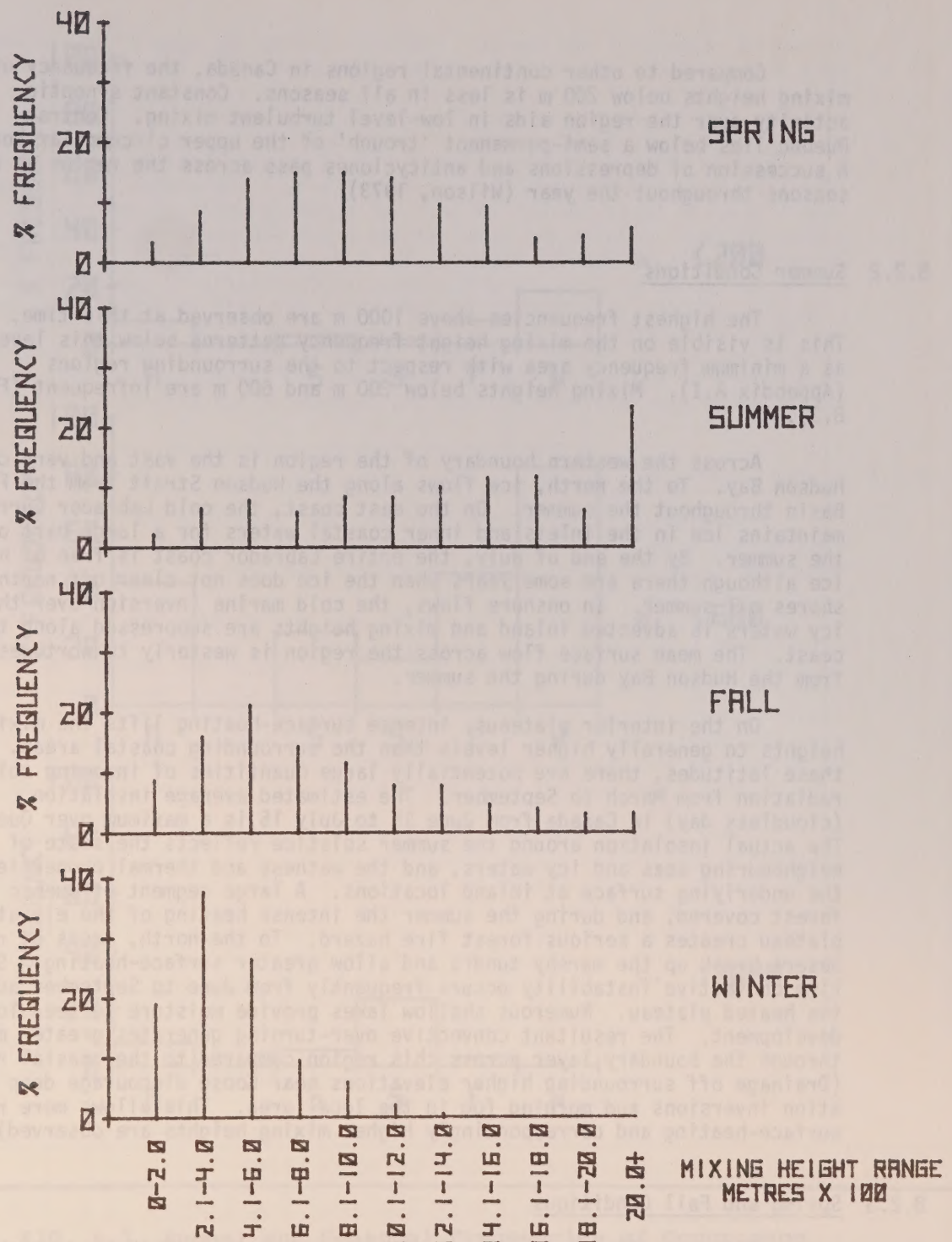


FIG. 8.2 SEASONAL FREQUENCY HISTOGRAMS OF SPECIFIED MAXIMUM MIXING HEIGHTS.

REGION: CENTRAL QUEBEC - LABRADOR
(Laurentian Plateau)

Compared to other continental regions in Canada, the frequency of mixing heights below 200 m is less in all seasons. Constant synoptic activity over the region aids in low-level turbulent mixing. Central Quebec lies below a semi-permanent 'trough' of the upper circumpolar vortex. A succession of depressions and anticyclones pass across the region at all seasons throughout the year (Wilson, 1973).

8.2.2 Summer Conditions

The highest frequencies above 1000 m are observed at this time. This is visible on the mixing height frequency patterns below this level as a minimum frequency area with respect to the surrounding regions (Appendix A.I). Mixing heights below 200 m and 600 m are infrequent (Fig. 8.3).

Across the western boundary of the region is the vast and very cold Hudson Bay. To the north, ice flows along the Hudson Strait from the Foxe Basin throughout the summer. On the east coast, the cold Labrador Current maintains ice in the inlets and inner coastal waters for a large part of the summer. By the end of July, the entire Labrador coast is free of heavy ice although there are some years when the ice does not clear off northern shores all summer. In onshore flows, the cold marine inversion over these icy waters is advected inland and mixing heights are suppressed along the coast. The mean surface flow across the region is westerly to northwesterly from the Hudson Bay during the summer.

On the interior plateaus, intense surface-heating lifts the mixing heights to generally higher levels than the surrounding coastal areas. At these latitudes, there are potentially large quantities of incoming solar radiation from March to September. The estimated average insolation (cloudless day) in Canada from June 15 to July 15 is a maximum over Quebec. The actual insolation around the summer solstice reflects the state of the neighbouring seas and icy waters, and the wetness and thermal properties of the underlying surface at inland locations. A large segment of Quebec is forest covered, and during the summer the intense heating of the elevated plateau creates a serious forest fire hazard. To the north, areas of rock desert break up the marshy tundra and allow greater surface-heating. Summertime convective instability occurs frequently from June to September across the heated plateau. Numerous shallow lakes provide moisture to feed local development. The resultant convective over-turning generates greater mixing through the boundary layer across this region compared to the coastal regions. (Drainage off surrounding higher elevations near Goose discourage deep radiation inversions and morning fog in the local area. This allows more rapid surface-heating and correspondingly higher mixing heights are observed).

8.2.3 Spring and Fall Conditions

The transition seasons have similar frequency distributions although frequencies of low mixing heights are slightly greater in fall (Fig. 8.2).

From March through to November, there is considerable solar radiation

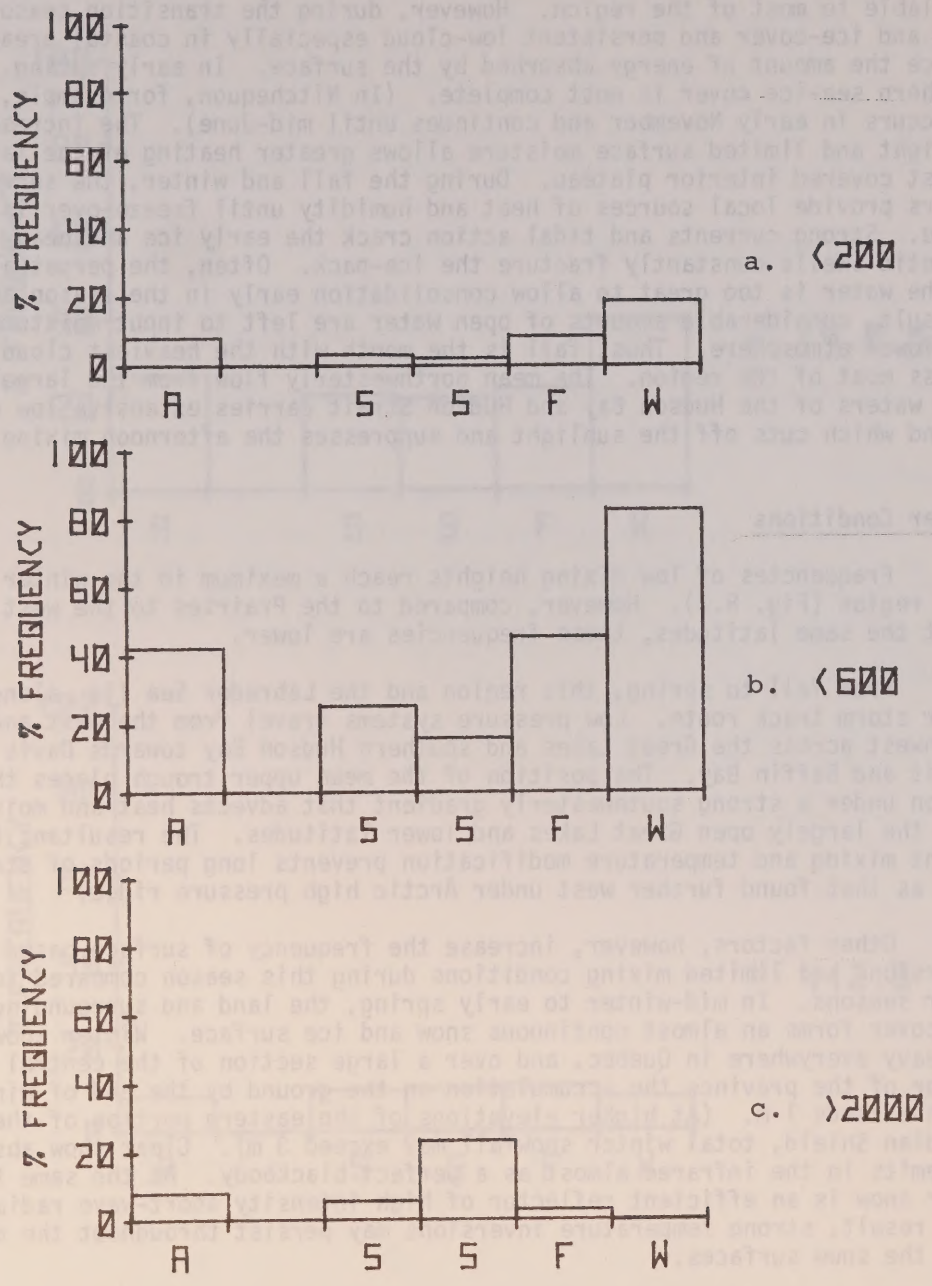


FIG. 8.3 Annual and Seasonal Frequencies of Occurrence of Maximum (Afternoon) Mixing Heights (m) for the Central Quebec - Labrador Region

available to most of the region. However, during the transition seasons, snow and ice-cover and persistent low-cloud especially in coastal areas reduce the amount of energy absorbed by the surface. In early spring, the northern sea-ice cover is most complete. (In Nitchequon, for example, freeze-up occurs in early November and continues until mid-June). The increased sunlight and limited surface moisture allows greater heating of the largely forest covered interior plateau. During the fall and winter, the surrounding waters provide local sources of heat and humidity until freeze-over is complete. Strong currents and tidal action crack the early ice and heavy Atlantic swells constantly fracture the ice-pack. Often, the perpetual motion of the water is too great to allow consolidation early in the season and as a result, considerable amounts of open water are left to input moisture into the lower atmosphere. Thus, fall is the month with the heaviest cloud cover across most of the region. The mean northwesterly flow from the largely open waters of the Hudson Bay and Hudson Strait carries extensive low cloud inland which cuts off the sunlight and suppresses the afternoon mixing heights.

8.2.4 Winter Conditions

Frequencies of low mixing heights reach a maximum in the winter in this region (Fig. 8.3). However, compared to the Prairies to the west at about the same latitudes, these frequencies are lower.

From fall to spring, this region and the Labrador Sea lie along a major storm track route. Low pressure systems travel from the west and southwest across the Great Lakes and southern Hudson Bay towards Davis Strait and Baffin Bay. The position of the mean upper trough places the region under a strong southwesterly gradient that advects heat and moisture from the largely open Great Lakes and lower latitudes. The resultant turbulent mixing and temperature modification prevents long periods of stagnation such as that found further west under Arctic high pressure ridge.

Other factors, however, increase the frequency of surface-based inversions and limited mixing conditions during this season compared to other seasons. In mid-winter to early spring, the land and surrounding sea cover forms an almost continuous snow and ice surface. Winter snowfall is heavy everywhere in Quebec, and over a large section of the central interior of the province the accumulation on the ground by the end of winter often exceeds 1 m. (At higher elevations of the eastern portion of the Canadian Shield, total winter snowfall may exceed 3 m). Clear snow absorbs and emits in the infrared almost as a perfect blackbody. At the same time, clear snow is an efficient reflector of high intensity short-wave radiation. As a result, strong temperature inversions may persist throughout the day over the snow surfaces.

8.3 MEAN TRANSPORT WIND SPEEDS THROUGH THE MIXED LAYER

Fig. 8.4 shows that winter has the highest frequencies of mean mixed-layer winds less than 4.0 m/s. The stronger winds (greater than 12.0 m/s) occur with almost the same frequency in all seasons. Limited horizontal ventilation occurs in winter because although the mean pressure gradient and frequency of synoptic systems are great at this time, strong radiation inversions above the snow covered surface prevents the downward transfer of momentum from the upper circulations.

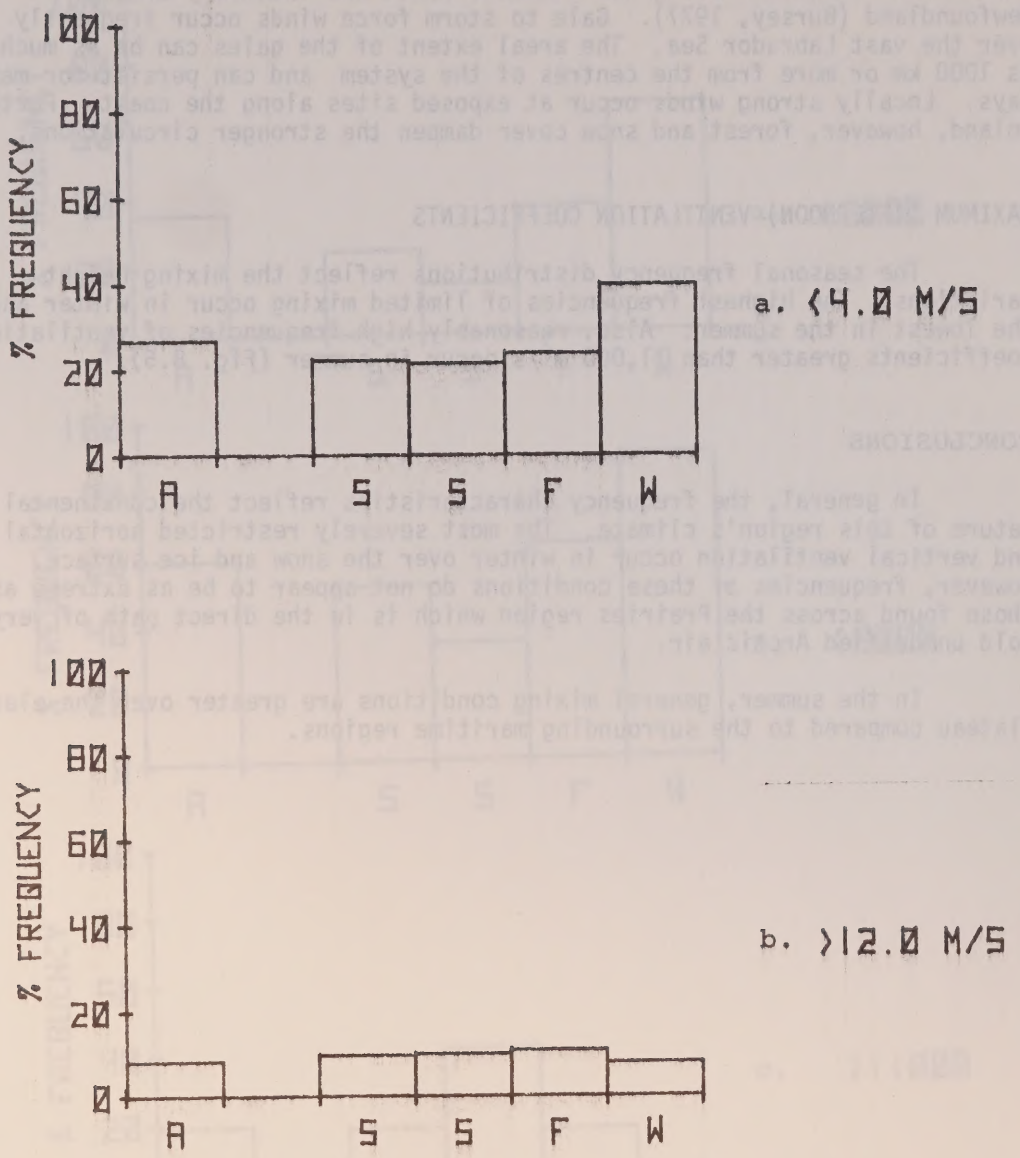


FIG. 8.4 Annual and Seasonal Frequencies of Occurrence of Mean Wind Speeds Through the Mixing Layer (m/s) for the Central Quebec - Labrador Region

From fall to spring many synoptic systems travel through the region. Others move northward along the Atlantic coast and intensify around Newfoundland (Bursey, 1977). Gale to storm force winds occur frequently over the vast Labrador Sea. The areal extent of the gales can be as much as 1000 km or more from the centres of the system and can persist for many days. Locally strong winds occur at exposed sites along the coast. Further inland, however, forest and snow cover dampen the stronger circulations.

8.4 MAXIMUM (AFTERNOON) VENTILATION COEFFICIENTS

The seasonal frequency distributions reflect the mixing height variations. The highest frequencies of limited mixing occur in winter and the lowest in the summer. Also, reasonably high frequencies of ventilation coefficients greater than 11,000 m^2/s occur in summer (Fig. 8.5).

8.5 CONCLUSIONS

In general, the frequency characteristics reflect the continental nature of this region's climate. The most severely restricted horizontal and vertical ventilation occur in winter over the snow and ice surface. However, frequencies of these conditions do not appear to be as extreme as those found across the Prairies region which is in the direct path of very cold unmodified Arctic air.

In the summer, general mixing conditions are greater over the elevated plateau compared to the surrounding maritime regions.

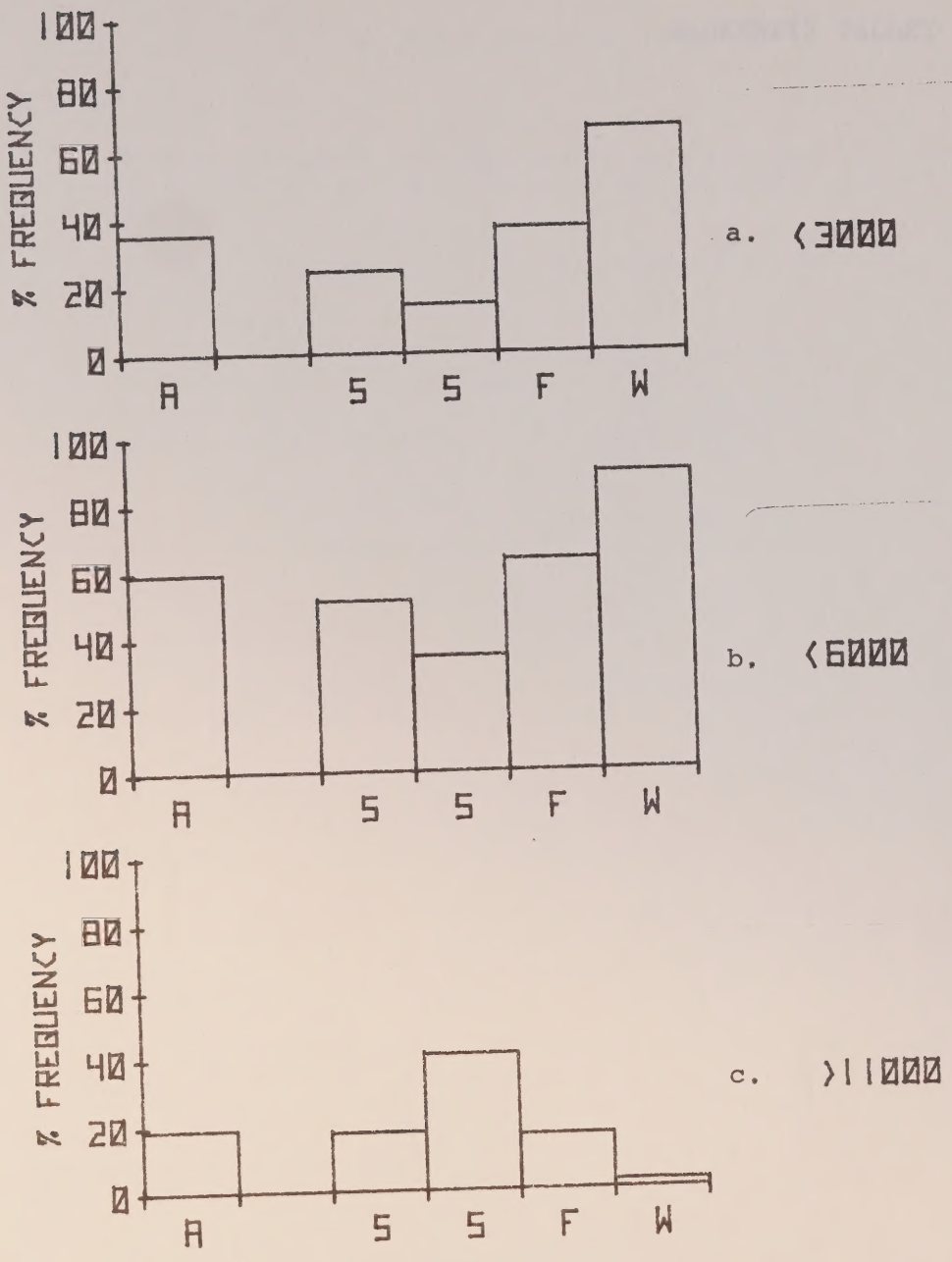


FIG. 8.5 Annual and Seasonal Frequencies of Occurrence of Afternoon Ventilation Coefficients (m^2/s) for the Central Quebec - Labrador Region

MACKENZIE VALLEY

CHAPTER 9

CHAPTER 9

MACKENZIE REGION VALLEY

9.1 INTRODUCTION

Some of the important meteorological and topographical elements which determine the air pollution potential in this region include the following:

1. The valley that makes up a large portion of the region (see Fig. 9.1).

2. Surrounding mountain ranges and their orientation with respect to the region (i) alter the wind speed and direction, (ii) generate turbulence (low-level and mountain wave), (iii) redistribute precipitation and cloud patterns, and (iv) produce lee subsidence warming.

3. Major bodies of water that affect the region, including (i) the Arctic Ocean and Beaufort Sea to the north, (ii) Great Bear Lake, Great Slave Lake and Lake Athabaska, and (iii) the Mackenzie River.

4. Mountain passes that channel the wind or permit warmer (and colder) airmasses to penetrate onto the opposite side.

5. The latitude mainly north of 60^{o}N which makes this one of the most northern continental regions in Canada.

6. The vegetation which is significant compared to the other regions of the Arctic. (The tree line is extended north of 60^{o}N along the valley; boreal forest in the south and southwest sections gives way to continental tundra and sparse vegetation in the north and east).

7. The upper flow which has a mean westerly component at all times of the year (northwesterly in the winter to southwesterly in the spring and summer) and is critical in the development of systems to the lee of the ranges and in the modification of airmasses.

8. The permafrost that penetrates to depths of 8 to 10 m in some locations. (The southern limit of permafrost has been determined as running from the confluence of the Liard and Mackenzie Rivers, eastward along the north shore of Great Slave Lake and thence in a general southeasterly direction, crossing the 60th parallel of latitude just east of Lake Athabasca. Only a small portion of the district of Mackenzie lies outside the permafrost area).

There are four rawinsonde stations available in the region: Inuvik, Norman Wells, Fort Smith and Fort Nelson. A complete description of the sites are available in Appendix D. Mesoscale climate controls play an important role in the processes below 1000 m at these sites and are worthwhile to consider when using data in this layer.

9.2 MAXIMUM (AFTERNOON) MIXING HEIGHTS

9.2.1 General Characteristics

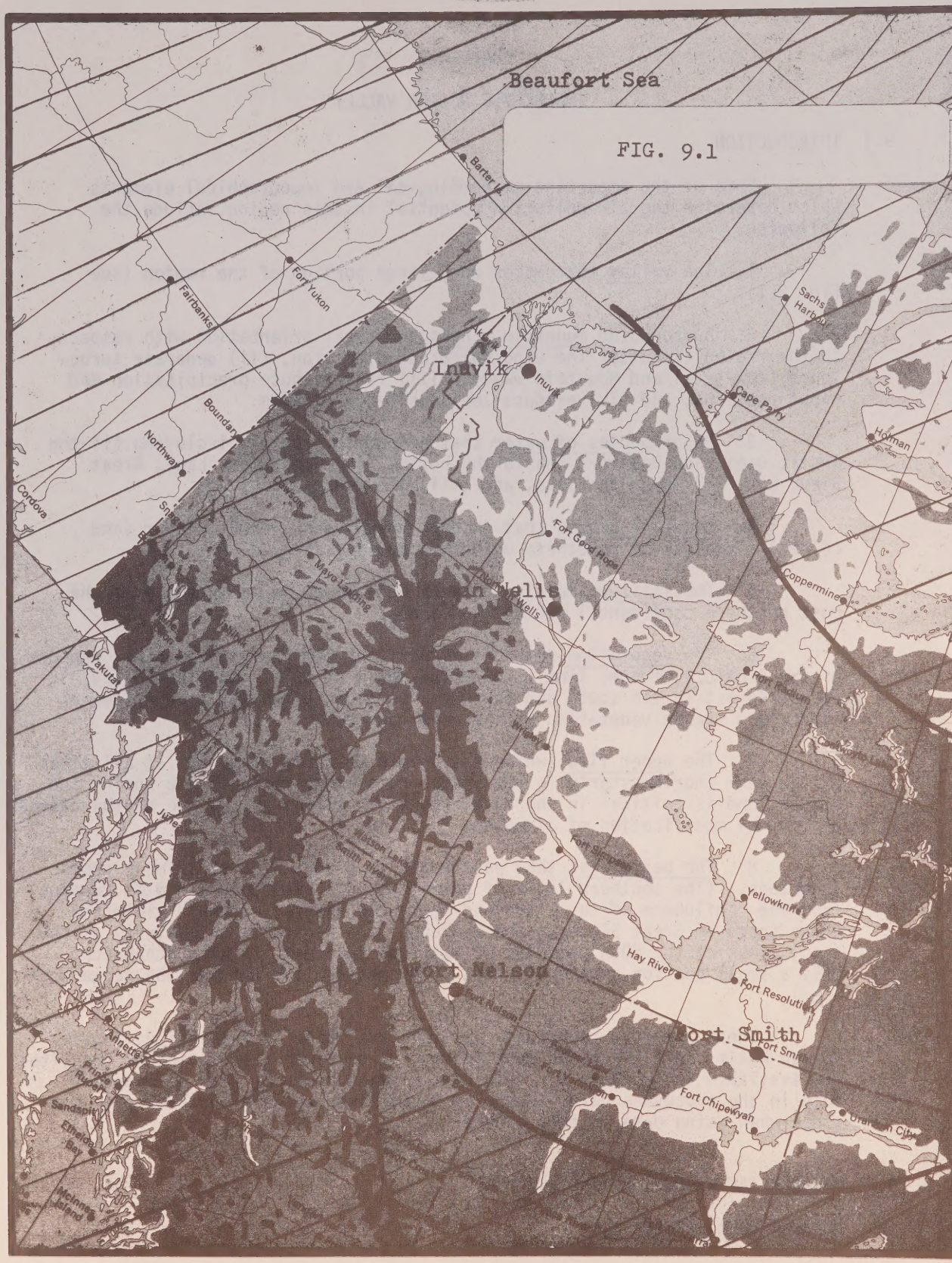


FIG. 9.1

● - rawinsonde station sites

MACKENZIE VALLEY REGION

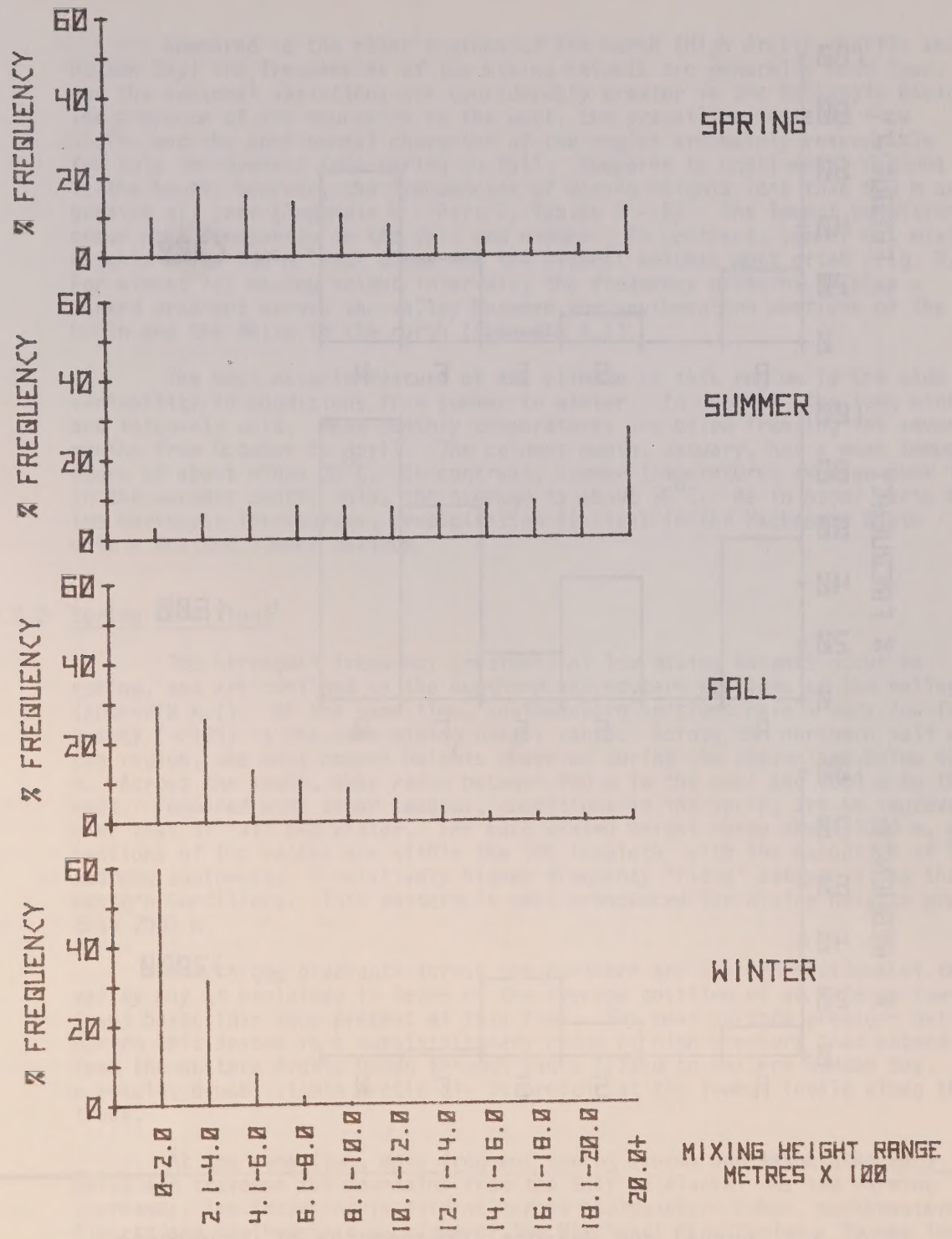


FIG. 9.2 SEASONAL FREQUENCY HISTOGRAMS OF SPECIFIED MAXIMUM MIXING HEIGHTS

REGION: MACKENZIE VALLEY

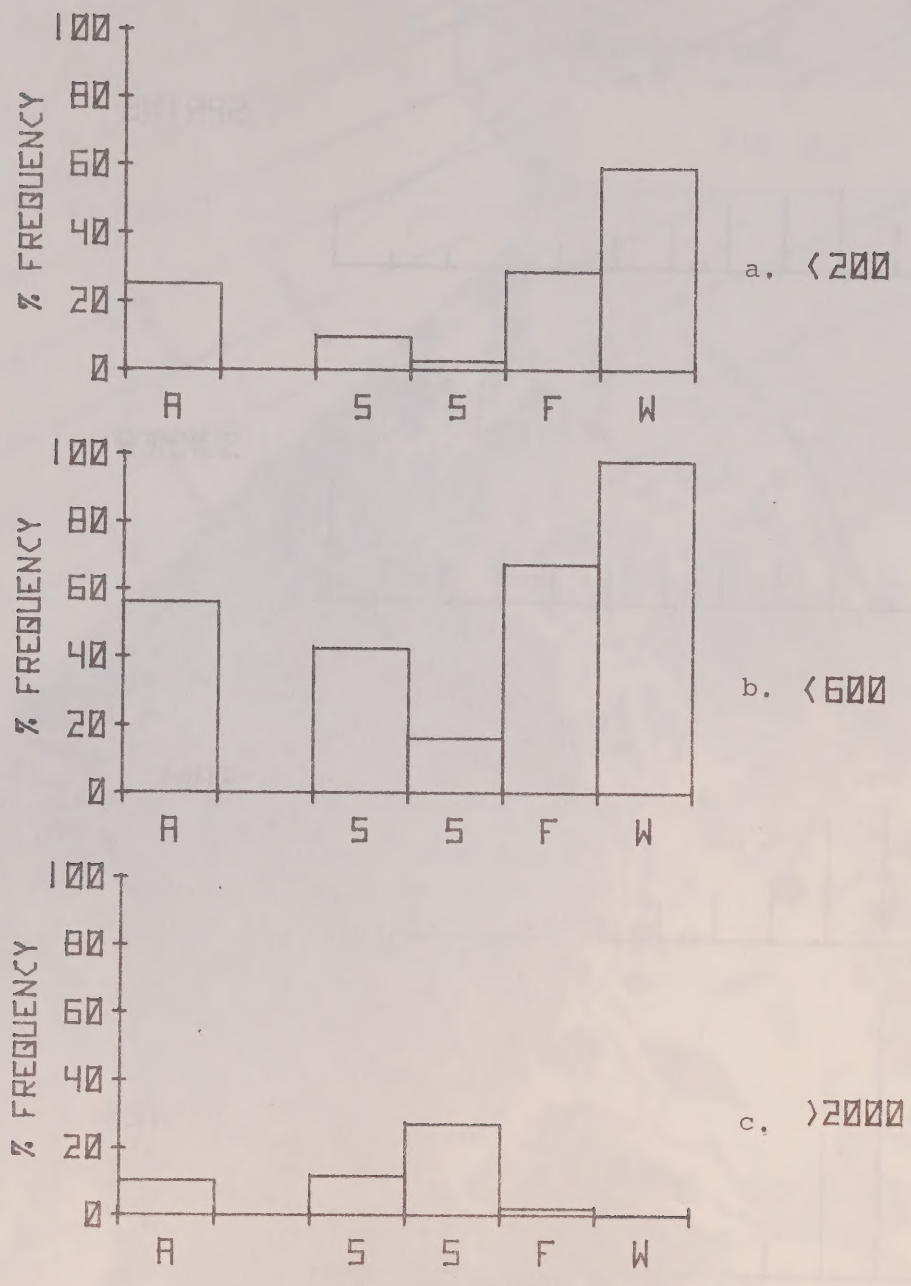


FIG. 9.3 Annual and Seasonal Frequencies of Occurrence of Maximum (Afternoon) Mixing Heights (m) for the Mackenzie Valley Region

Compared to the other regions of the north (High Arctic, Baffin and Hudson Bay) the frequencies of low mixing heights are generally much less, and the seasonal variations are considerably greater in the Mackenzie Basin. The presence of the mountains to the west, the prevailing westerly flow aloft, and the continental character of the region are mainly responsible for this improvement from spring to fall. Compared to continental regions in the south, however, the frequencies of mixing heights less than 600 m are greater all year (Appendix C - Part 2, Tables 5 - 8). The lowest conditions occur most frequently in the fall and winter. In contrast, summer has mixing heights below 600 m least often and the highest heights most often (Fig. 9.3). For almost all mixing height intervals, the frequency patterns display a marked gradient across the valley between the southwestern sections of the basin and the delta to the north (Appendix A.I).

The most notable feature of the climate in this region is the wide variability in conditions from summer to winter. In general, the long winters are intensely cold. Mean monthly temperatures are below freezing for seven months from October to April. The coldest month, January, has a mean temperature of about minus 30°C. In contrast, summer temperatures average over 10°C. In the warmest month, July, the average is about 20°C. As in other parts of the Northwest Territories, precipitation is light in the Mackenzie Basin with a decided summer maximum.

9.2.2 Spring Conditions

The strongest frequency gradients of low mixing heights occur in spring, and are confined to the northern and eastern sections of the valley (Appendix A.I). At the same time, southwestern sections have a very low frequency (< 10%) in the same mixing height range. Across the northern half of the region, the most common heights observed during the season are below 400 m. Across the south, they range between 400 m in the east and 1000 m to the west. Compared with other seasons, conditions in the spring are an improvement over that of fall and winter. For each mixing height range above 1000 m, all sections of the valley are within the 10% isopleth with the exception of the extreme southwest. A relatively higher frequency 'ridge' extends along the Western Cordillera. This pattern is most pronounced for mixing heights greater than 2000 m.

The strong gradients across the northern and eastern sections of the valley may be explained in terms of the average position of an intense low-level baroclinic zone present at this time. The mean surface pressure pattern during this season is a quasistationary ridge of high pressure that extends from the western Arctic Ocean through Banks Island to western Hudson Bay. As a result, dense, stable Arctic air is present at the lowest levels along this track.

At the same time, more frequent spring storms and associated warm, moist air traverse the mountains from the Gulf of Alaska. As the warming increases, lee troughing is evident across southeastern Yukon, northwestern Alberta and southwestern sections of the Northwest Territories. To the lee of the mountains and initiated by divergence in the upper flow, a favoured location for cyclogensis is north of Fort Nelson and west of Great Slave Lake. At this time of year, there is a major southwesterly componentin the flow normal to the mountain range. The resultant subsidence and vertical stretching warms the descending Pacific airmass to higher temperatures. Most of this very mild

airmass passes over the wedge of cold Arctic air to the north and east. At the interface of the two contrasting airmasses, pronounced low-level inversions occur.

Other factors reinforce these low-level inversions. First of all, the net radiation received in the Mackenzie Valley at this time is reduced by overrunning cloud from the more frequent Pacific storms. Moisture from these fast moving synoptic systems generate extensive upslope stratus along the valley. In addition, the mean position of the Arctic ridge results in a net outflow against the mountains. In April, the mean solar radiation received at the ground (including the effect of mean cloudiness) indicates a net gain across the south, and a net loss in the north (Burns, 1973). There is also an east-west radiation variation. Along the Mackenzie Valley at 125^{0}W, there is a radiation minimum and a contrasting maximum over the western mountains. This is partially due to widespread cloud and precipitation to the north and east of developing systems on the lee side of the mountains, and the upslope factor as described above.

Secondly, in the vicinity of the coldest airmass, variations in the optical transparency of the atmosphere at lower levels are due to high ice-crystal concentrations. The increasing number of open leads during the season result in considerable fog (or ice fog) and stratus near Great Bear Lake, Great Slave Lake and Lake Athabaska, and along the Mackenzie River.

Additional factors strengthen the temperature differential between the airmasses including the ground cover, the resultant albedo and the corresponding changes in these parameters as the season progresses. During the spring, the snow and ice cover gradually recedes from the south. In the north, the Beaufort Sea is principally ice covered until late in the season. Thus, the albedo (in April) is 40% in the south, increasing northward to greater than 70% over the Beaufort Sea (Burns, 1973).

The combination of the preceding factors leads to intense inversions in the vicinity of the mean baroclinic zone along eastern and northern sections of the valley. Since variations in the net insolation are a function of the cloud cover and the reflective characteristics of the surface, much lower temperatures (and correspondingly low mixing heights) occur at the edge of the coldest airmass. Also, by the time the warmer westerly air reaches the eastern sections, considerable modification at lower levels has taken place through contact with the underlying surface and radiational cooling.

The higher mixing heights across the southwestern sections of the basin can be explained in terms of the mean upper flow and the associated lee cyclogensis. As mentioned earlier, during spring the upper flow becomes more zonal compared to the northwesterly flow aloft that occurs in winter. By May, a mean ridge position develops along the Yukon border resulting in a vital southwesterly component normal to the mountain range. Along the storm track and lee cyclogensis zone across the south, greater turbulent mixing and convective instability develop. This activity breaks down the low-level inversions and generally higher mixing heights are observed. Less cloud in the lee subsidence allows greater sunshine to reach the surface. The net insolation is still greater in the south due to the latitude and sun-angle, and to the lower reflectivity from the thawing landscape. South of the mean lee low position, repeated surfacing of Pacific air occurs. (A maximum of net radiation extends from Hay River through to the southern Yukon (Burns, 1973).)

9.2.3 Summer Conditions

The spring and summer patterns across the valley are similar at low mixing heights (<400 m). In the summer, the gradient (mainly to the north and northeast) is less extreme (Appendix A.I). For levels below 1000 m, only the northeastern sections of the region have frequencies greater than 10%. The greatest percentage frequency of mixing heights less than 200 m continues to be along the Arctic coastline. Southwestern sections of the valley have the lowest relative frequency at this level (<2%).

From Fig. 9.3, it is apparent that this season has the best conditions for vertical diffusion. The low frequency of low mixing heights in the southwestern part of the Northwest Territories is in agreement with the study by Munn et al (1970). They concluded that no serious pollution potential should develop in this area despite the fact nocturnal radiation inversions occur at least 60% of the time.

A marked difference from the other seasons is the higher frequency of heights above 2000 m over most sections of the valley (Fig. 9.3 c). (The maximum occurs along the mountains and the frequencies decrease eastward from the divide). Through June and July, there is a mean upper ridge along the Yukon border. By August, the flow aloft becomes more zonal westerly. As in the spring, a westerly (or southwesterly) component aloft causes subsidence warming to the lee of the divide. Warm maritime Arctic air modifies to maritime Polar air. Occasionally maritime Tropical air will invade southern sections ahead of a vigorous frontal low pressure system or modify beneath the strong upper-level ridge (Burns, 1973). In addition, the mean surface pressure pattern during this season, produces a net northwesterly downslope wind across the central and upper valley from June to August. The resultant ameliorating effect on the temperatures, together with increased daylight make this a peak period for thermal instability. These factors support the observed annual minimum of low mixing heights and maximum of heights above 2000 m.

The gradient to higher frequencies across the northeast reflects the continued presence of the coldest air at low levels in this area. This is due to the slowly retracting snow and ice cover in the early part of the summer, the numerous cold lakes and channels in the tundra, and the proximity to the very cold coastal waters of the Beaufort Sea. The outflow from the high pressure area over the Arctic Ocean results in a mean northerly onshore current that helps suppress mixing heights along the coast. Similarily, sea-breezes will carry cold moist air from over the icy water inland over the heated terrain. (Slightly higher heights are observed at Inuvik because the Caribou Hills act as a fog barrier.)

During the summer, incoming solar energy reaches an annual maximum, peaking in June. The low sun-angle at these higher latitudes is compensated for by the increased length of the day. Thus, there is a net gain of solar radiation for the entire region (with decreasing values to the north). The albedo shows a marked gradient southward from the ice to open water to bare land. The forest areas across the southwest sections of the valley have a low albedo (3 - 10%). The very hot, dry conditions make this a peak forest fire season and thick smoke periodically cuts off the bright sunshine. On the average, however, the combination of maximum net insolation and minimum

albedo enable southwestern sections to have the highest annual frequency of mixing heights greater than 1000 m, and thus the greatest vertical diffusion for the entire region.

9.2.4 Fall and Winter Conditions

The fall and winter frequency patterns are similar and dominate the annual patterns at lower mixing height levels (Appendix A.I). In these cases, a 'trough' of higher frequency values extends southward along the valley. A strong north-south frequency gradient places the highest values across the north. In the winter, Sachs Harbour has 90% less than 200 m.

In both seasons, the greatest concentration of mixing heights is below 600 m, (Fig. 9.3 b). In the winter, the frequencies drop off rapidly to zero above this level (Fig. 9.2). In the fall, only the southwestern sections of the valley (Great Slave Lake and westward) have measurable frequencies of heights above 600 m but these drop off significantly for levels above 1000 m.

There are several inter-related factors responsible for the pronounced seasonal change in the low mixing height frequencies, especially along the upper valley.

1. The Controlling Weather Patterns:

First of all, the mean position of the upper ridge over the western valley and Yukon retrogresses back to the Gulf of Alaska coast from September to November, and remains there until March. At the same time, the quasi-stationary Arctic vortex develops near Baffin Island. The resultant increasing cyclonic flow between the western ridge and deepening cold low to the east places the valley in a strong northwesterly gradient aloft from December to February. Shortwaves embedded in the flow support systems that advance the southward intrusion of deep cold air as the season progresses into the continuous Polar night.

From October to December, the surface reflection of the upper ridge is an anticyclone that builds southward from the Arctic Ocean. A mean position directly along the valley remains until January, and then begins to edge eastward. The outflow from the high pressure ridge presses the Arctic airmass against the mountains in western sections of the basin. The cold, dense air at lower levels of the valley deepens from autumn to winter. At the same time, this dome of Arctic air forms a block to migrating frontal lows from the west. The penetration of milder maritime air from the Gulf of Alaska will cause major storms east of the divide. Similarily, the Aleutian low will send off secondary lows into the Beaufort Sea giving intense blizzards from January to March.

2. The Airmasses:

The latitudinal variation in the sun's heating rate causes a drastic reduction in solar energy and resultant freeze-up from September to December. Outbreaks behind the autumn cyclones become progressively colder. Maritime Arctic air is replaced by a colder airmass (cmA), and this becomes continental Arctic by mid-winter.

The resultant cold air pools in the valleys and becomes more difficult

to displace or modify. Overriding warmer air associated with the Pacific systems reinforce already existing low-level inversions. A good example of this periodically occurs at Fort Nelson where extreme variations in the temperature profile may be reported in the lowest 1000 m above the surface.

3. The Insolation:

Incoming solar radiation is a major factor in determining airmass characteristics that affect pollution potential parameters.

a) Solar Energy Input - The strong gradient going north to higher frequencies of low mixing heights can be explained in terms of the seasonal variation in the amount of useful daylight. This lowers from a range of 20 hours at 60°N and 24 hours at Sachs Harbour in the summer, to 6 hours and zero hours, respectively in the winter. A little energy is available during the Arctic twilight in the fall (or in the winter in the south). In the north, however, a net depletion takes place throughout the winter.

b) Surface Cover - Increasing snow and ice during the transition from summer to winter result in a further depletion of the net solar radiation. Since snow cover has a high albedo most of the incident light is reflected back into space. Reflection from the tundra surface varies from about 25% in the early summer to about 80% when the snow cover arrives (Findlay and Triedl, 1975). Furthermore, since it radiates as a blackbody, extremely low temperatures are attained at its surface.

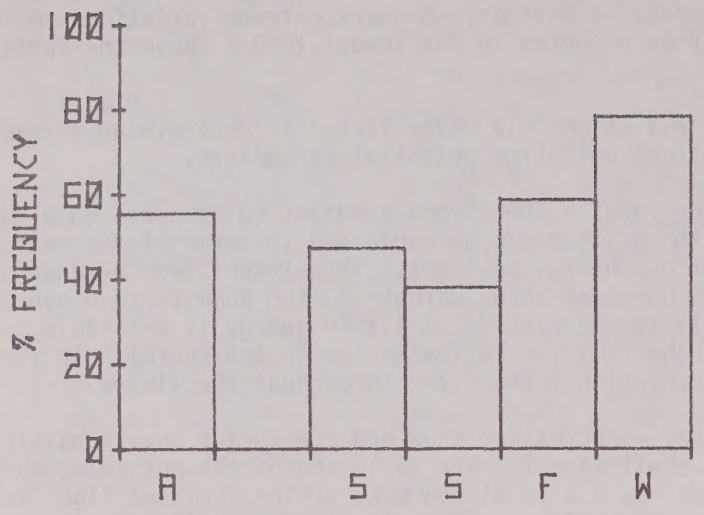
c) Heat and Moisture Sources - September to November is considered the stormiest part of the year. A secondary maximum occurs in the late spring (Burns, 1973). The could cover associated with these systems achieves a maximum in late autumn and lowers the amount of radiation reaching the ground by about 1/3. In addition, moisture is available from the open water areas during the early fall. In winter, the sources are limited to isolated open leads and settlements. During the transition period, the air temperature is colder than the water in the unfrozen lakes and rivers which act as heat reservoirs. Resultant 'steaming' from the relatively warmer waters injects considerable moisture into the air. Extensive cloud and snowflurry activity occur to the 'lee' of the open water areas. Large ice-crystal concentrations and dense ice-fog around leads or due to moisture advected in by systems, further reduce the limited insolation east of the mountains.

In summary, the three factors described above produce a high frequency of low mixing heights during the fall and winter seasons. This pattern follows the topography of the river valley where the deepest layer of cold Arctic air stagnates for long periods of time.

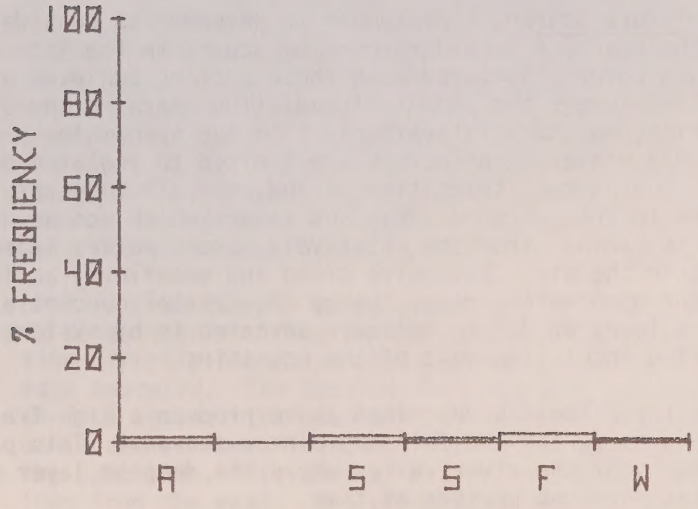
9.3 MEAN TRANSPORT WIND SPEEDS THROUGH THE MIXING LAYER

9.3.1 General Characteristics

Annually (Fig. 9.4), over half of the occurrences of mean winds are in the calm to light wind speed category. In this range, a maximum frequency 'trough' of frequencies greater than 60% follows the valley from Inuvik to Fort Nelson (Appendix A.II). These light winds are more frequent in the fall and winter compared to other seasons and compared to other regions of Canada (Appendix C - Part 2, Tables 13 - 16). Mean winds greater than 12.0 m/s are



a. <4.0 M/S



b. >12.0 M/S

FIG. 9.4 Annual and Seasonal Frequencies of Occurrence of Mean Wind Speeds Through the Mixing Layer (m/s) for the Mackenzie Valley Region

uncommon. (NOTE: mean mixed layer wind speeds are not calculated in cold advection cases in this study).

Shaw et al (1972) concluded that British Columbia, northern Alberta and the southern Yukon experience the greatest number of occurrences of persistent light surface winds of all the regions of Canada.

9.3.2 Fall and Winter Conditions

Around 90% of the cases have mean wind speeds less than 8.0 m/s during these seasons (Appendix B, Table 9.2). In these relatively light wind speed ranges, the higher frequency 'trough' that extends down the valley during these seasons governs the annual pattern. For mean mixed layer wind speeds greater than 8.0 m/s, the frequencies drop off to less than 10%. Above 12.0 m/s the frequencies are near zero.

Although September to November is considered the stormiest part of the year, well-defined cyclones and anticyclones do not move as rapidly. The mean anticyclonic pattern and its inherent light winds are interrupted only on occasion by frontal cyclones. During the winter, the frequency of calms between the storms increases. As a result, the largest extremes occur at this time: while the most severe surface winds are reported during this season the average winds are relatively light.

Other factors responsible for the high frequency of light mean winds along the valley at this time of year are listed below:

1. Cold, dense air associated with the Arctic High maintains stable conditions throughout the valley. Warmer, lighter air and associated gradient or gusty winds usually ride over the colder layer.

2. Treed or sheltered valley sites along the basin pool the colder air and compound the above effect. For example, the dense forest at the Fort Nelson valley site protects the station from strong winds.

3. Local circulations due to orographic effects that increase the turbulent wind speed during the spring and summer do not reach the valley floor.

East of the Mackenzie Valley (over the Barrens), slightly higher mean winds are more frequent. The lack of physically retarding features (that is, the open lakes and treeless tundra) enable stronger winds to develop.

9.3.3 Spring and Summer Conditions

The maximum frequency 'trough' is still evident on the calm to light mean wind speed patterns. However, the frequencies although a relative maximum, are much less than the corresponding fall and winter values. Frequencies of mean winds between 4.0 to 12.0 m/s are the highest in spring and summer (Appendix B, Table 9.2).

In spring the rapid passage of frontal cyclones and the extreme airmass temperature contrasts typical of the season result in stronger

circulations and higher mean wind speeds through the mixing layer. Anti-cyclones and associated calms do not remain long over a given location. In addition, more frequent strong and gusty winds reach the surface in the subsiding westerly flow over the mountains. Often, this effect is not felt in deep valleys due to residual cold air trapped there. As a result, the frequencies of light winds (< 4.0 m/s) in spring are slightly higher than that of summer.

In summer, the relatively lower frequency (annual minimum) of calm winds can be attributed to increased instability at this time. Maximum surface-heating increases the turbulent eddies through the afternoon mixing layer and gives stronger mean winds in spite of the weak synoptic pattern. Also, the anabatic and katabatic valley winds, and sea-breeze currents off the lakes increase the mean mixed layer wind speeds.

9.4 MAXIMUM (AFTERNOON) VENTILATION COEFFICIENTS

Reflecting the low mixing height frequencies ventilation coefficient ranges below 3000 m^2/s show greater seasonal variation and have lower frequencies than that of the other northern regions.

Summer has the best vertical and horizontal diffusion. Less than a quarter of the cases occur below 3000 m^2/s (Fig. 9.5 a). In the winter, however, conditions are comparable to the High Arctic. For lower ventilation coefficients, a pattern of higher frequencies extends down the valley on the spring, fall and winter charts but is absent in the summer (Appendix A.III).

The combination of frequent low mixing heights and light mean mixed layer winds along the valley from fall to spring result in the high frequencies of ventilation coefficients less than 1000 m^2/s. Eastern sections of the valley, just east of Great Slave and Great Bear Lakes, have slightly lower frequencies than the rest of the valley. For example, in the fall Fort Smith has 25% compared to over 50% at Fort Nelson. This becomes 63.5% to 87.3%, respectively, in the winter.

Above 2000 m^2/s, values drop off to about 10% in the fall, and to less than 5% in the winter for most of the valley. (Fort Smith is slightly higher).

9.5 CONCLUSIONS

The main reasons for variations within the region and between seasons are summarized below:

1. Latitude and length of the Polar night.
2. Extent and duration of the snow and ice cover.
3. Position of the Arctic high pressure ridge.
4. Proximity to the mainly frozen Beaufort Sea.
5. Lee cyclogensis and subsidence warming to the south.

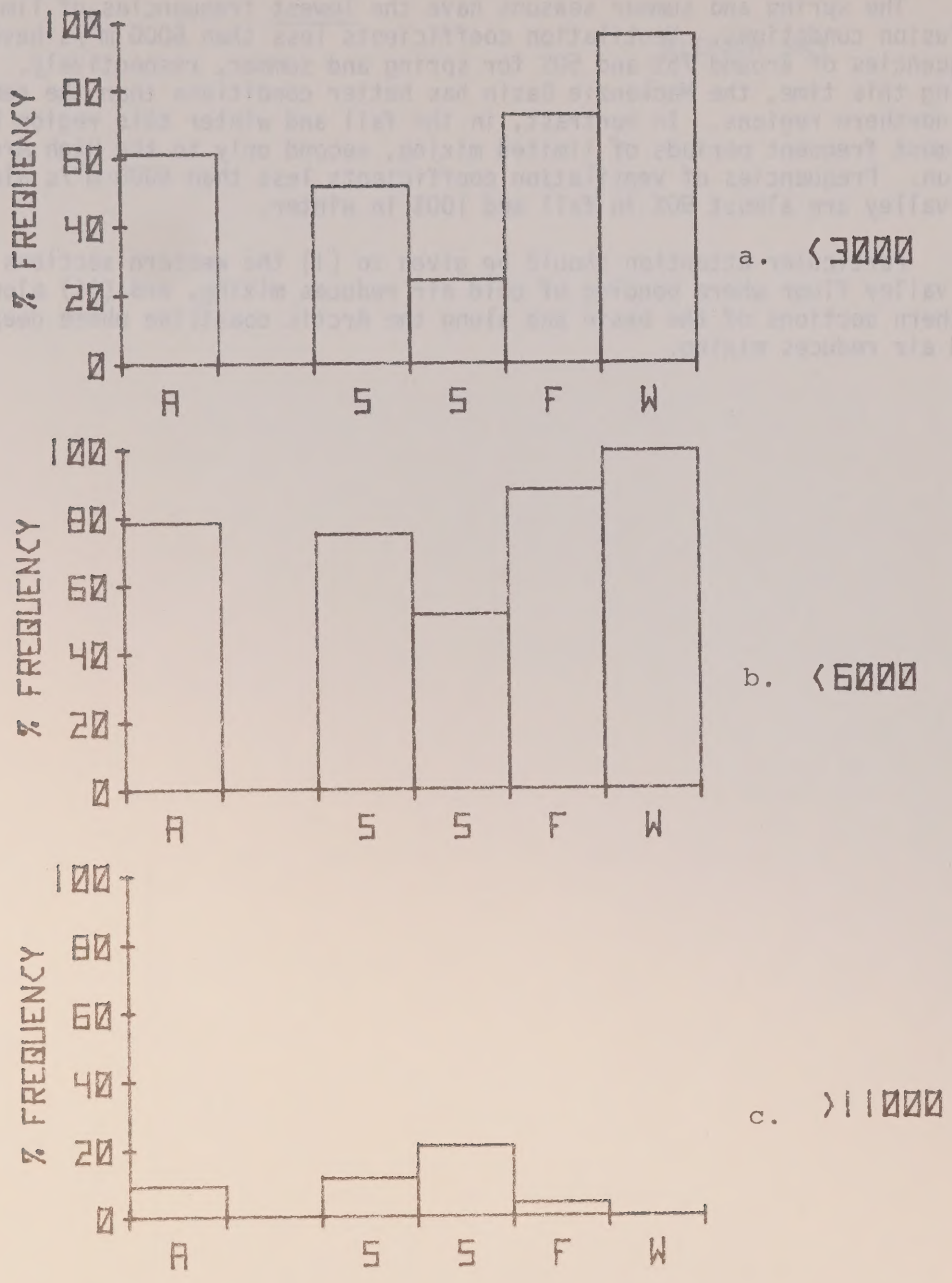


FIG. 9.5 Annual and Seasonal Frequencies of Occurrence of Afternoon Ventilation Coefficients (m^2/s) for the Mackenzie Valley Region

The spring and summer seasons have the lowest frequencies of limited diffusion conditions. Ventilation coefficients less than 6000 m^2/s have frequencies of around 75% and 50% for spring and summer, respectively. During this time, the Mackenzie Basin has better conditions than the remaining northern regions. In contrast, in the fall and winter this region has the most frequent periods of limited mixing, second only to the High Arctic region. Frequencies of ventilation coefficients less than 6000 m^2/s along the valley are almost 90% in fall and 100% in winter.

Particular attention should be given to (i) the western sections of the valley floor where ponding of cold air reduces mixing, and (ii) along northern sections of the basin and along the Arctic coastline where deeper cold air reduces mixing.

HUDSON BAY

CHAPTER 10

CHAPTER 10

HUDSON BAY REGION

10.1 INTRODUCTION

The Hudson Bay region includes all of Hudson Bay, Southampton Island, the eastern barrens, the Hudson Bay lowlands, James Bay and the west coast of Quebec (Fig. 10.1).

Three main physiographical features distinguish this region from all others in Canada, and determine the significantly different characteristics of the lower atmosphere.

1. The expansive Hudson Bay is a large, open body of cold water in the summer, and an almost entirely ice-covered surface in the winter.

2. The flat, boggy lowland plains that border the bay on all sides have mainly tundra vegetation. The bay and lowlands taken together comprise an almost uniform surface of vast areal extent, at or near sea level.

3. The region spans almost 15 degrees of latitude, centered near 60 degrees north.

The Hudson Bay region is well-documented by six rawinsonde stations surrounding the bay: Baker Lake, Coral Harbour, Inoudjouac, Moosonee, Trout Lake and Churchill. (Site descriptions are given in Appendix D for each of these stations). In spite of the fairly uniform characteristics of the region, the same data limitations in the lowest 1000 m above the surface apply to these sites.

10.2 MAXIMUM (AFTERNOON) MIXING HEIGHTS

10.2.1 General Characteristics

Relative to the prairies and the Mackenzie Valley to the west, and Quebec and southern Baffin Island to the east Hudson Bay has lower mean mixing heights all year. A 'trough' of relatively higher frequencies of low mixing heights projects across the region from the High Arctic Islands, (Appendix A.I). These lower mixing height values are readily apparent on the seasonal frequency distributions in Fig. 10.2. Fig. 10.3 b indicates that over 60% of the cases are less than 600 m in all seasons except summer. The frequency of conditions above 2000 m is very small at all times (Fig. 10.3 c).

10.2.2 Winter Conditions

Winter has the highest frequency of conditions below 200 m, and over 90% of the cases are below 600 m (Fig. 10.3). From Fig. 10.2, the highest frequencies occur in the lowest 400 m.

FIG. 10.1

HUDSON BAY REGION

● - rawinsonde station sites

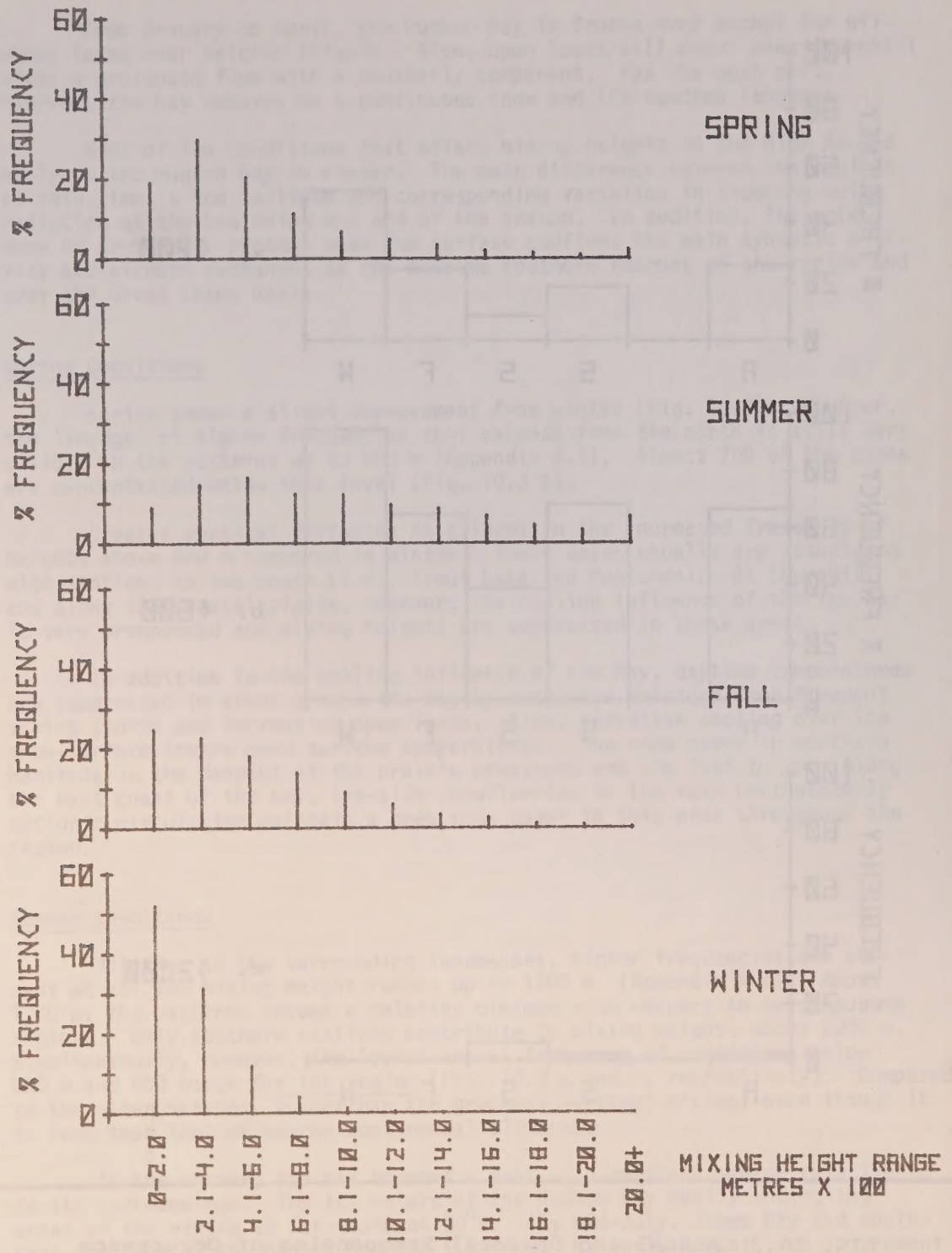


FIG. 10.2 SEASONAL FREQUENCY HISTOGRAMS OF SPECIFIED MAXIMUM MIXING HEIGHTS

REGION: HUDSON BAY

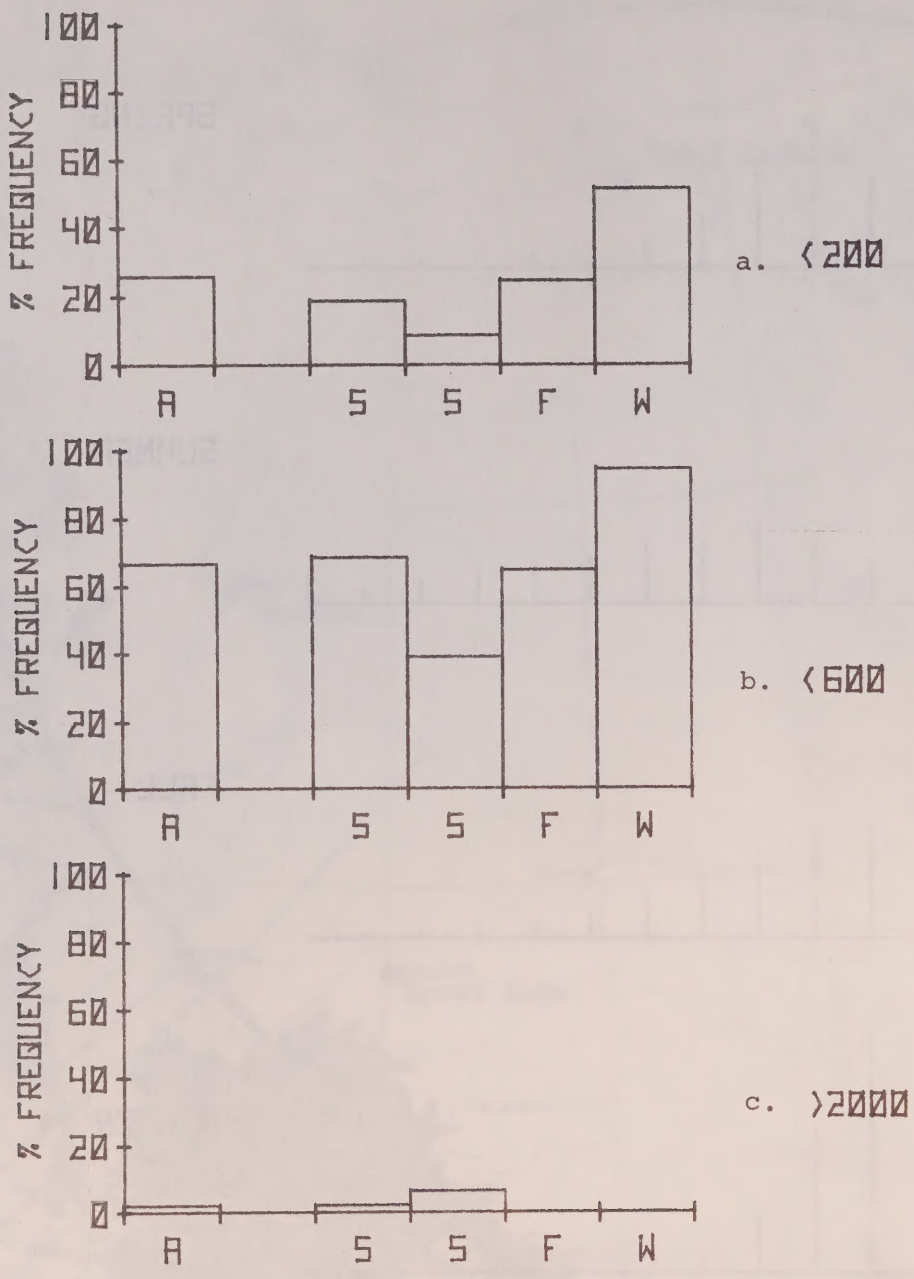


FIG. 10.3 Annual and Seasonal Frequencies of Occurrence of Maximum (Afternoon) Mixing Heights (m) for the Hudson Bay Region

From January to April, the Hudson Bay is frozen over except for offshore leads near Belcher Islands. Also, open leads will occur near Churchill after a prolonged flow with a southerly component. For the most part, however, the bay behaves as a continuous snow and ice-covered landmass.

Most of the conditions that affect mixing heights in the High Arctic apply to the Hudson Bay in winter. The main difference between the regions at this time is the latitude and corresponding variation in incoming solar radiation at the beginning and end of the season. In addition, the cold dome of Arctic air present near the surface confines the main synoptic activity and airmass exchanges to the extreme southern reaches of the region and over the Great Lakes Basin.

10.2.3 Spring Conditions

Spring shows a slight improvement from winter (Fig. 10.2). However, the 'trough' of higher frequencies that extends from the north is still very visible in the patterns up to 600 m (Appendix A.I). Almost 70% of the cases are concentrated below this level (Fig. 10.3 b).

Greater vertical diffusion is evident in the increased frequency of heights above 600 m compared to winter. These cases usually are associated with stations to the south (i.e., Trout Lake and Moosonee). At Churchill and along the coastal plains, however, the cooling influence of the icy bay is very pronounced and mixing heights are suppressed in these areas.

In addition to the cooling influence of the bay, daytime temperatures are suppressed in areas around the bay by extensive moisture from frequent spring storms and increasing open leads. Also, radiative cooling over the snow-surface lowers mean surface temperatures. The snow cover in northern Manitoba is the deepest of the prairie provinces and the last to go. Along the east coast of the bay, lee-side snowflurries in the mean northwesterly cyclonic circulation maintain a deep snow cover in this area throughout the season.

10.2.4 Summer Conditions

Relative to the surrounding landmasses, higher frequencies are evident at all low mixing height ranges up to 1200 m (Appendix A.I). Above 1200 m, the patterns become a relative minimum with respect to neighbouring regions. Only southern stations contribute to mixing heights above 2000 m. Simultaneously, however, the lowest annual frequency of conditions below 200 m and 600 occur for the region (Fig. 10.3 a and b, respectively). Compared to the other seasons, summer has the greatest vertical mixing, even though it is less than that of nearby continental climates.

In the summer, the bay becomes a vast cold moisture source relative to its surroundings. The icy waters of the Hudson Bay modify encircling areas of the region as far south as 50°N. (By mid-July, James Bay and southeast portions of the Hudson Bay are ice-free. By early August, ice is present in south-western Hudson Bay only. In most years, by September it is all clear.)

Along the east coast of the bay, cold, moist air from over the surface of the water is advected inland in the mean northwesterly onshore flow. On the west coast, the net 'thermal' low over the prairies and barrens through mid-summer produces an easterly onshore flow. This penetrating dampness drastically reduces insolation and surface-heating along coastal sites. Moreover, the Canadian Shield surrounding the bay is heavily glaciated and has numerous lakes and poor drainage (Longley, 1972). Limited surface-heating and thermal activity takes place across the marshy lowlands and permafrost regions.

As a result, mixing heights over the region are generally suppressed compared to continental regions on either side.

10.2.5 Fall Conditions

The fall frequency distribution is similar to spring (Fig. 10.2). Frequencies of mixing heights below 600 m, however, are slightly less.

As mentioned earlier, the Hudson Bay is completely ice-free in September in most years. The colder airmasses now sweeping over the region from the north and west absorb moisture from the open water. In the late fall and early winter, the surface water temperature is relatively warmer than the Polar air crossing the bay from the west and Arctic air penetrating from the north. Modification from the underlying surface takes place up to 3000 m (Burbidge, 1951).

Evaporation from the bay into the colder airmasses produces maximum cloudiness during this season over areas of the Canadian Shield (Longley, 1972). A mean cloud cover of 70% is present in northern Manitoba in November. More intensive synoptic activity in conjunction with the heating from below produces considerable turbulent mixing in the boundary layer and extensive stratocumulus.

Until freeze-over is complete, the presence of this heat and moisture source is responsible for the heavy cloud and snowfall activity along the east coast of Hudson Bay and James Bay. In October, the ice begins to reform across the northwest and west first, and the southeast last. The Quebec shores are frozen by mid-November and James Bay by December.

10.3 MEAN TRANSPORT WIND SPEEDS THROUGH THE MIXED LAYER

10.3.1 General Characteristics

The most notable difference between the Hudson Bay region and the Mackenzie Valley or high Arctic is the increase in frequencies of mean winds greater than 12.0 m/s (Appendix C - Part 2, Tables 17-20). The annual frequency in this range is many times greater than that of the Mackenzie Valley and almost twice that of the High Arctic. In all three regions, however, these stronger mixed layer winds occur most often in the fall.

Generally greater horizontal motion takes place through the lowest layers of the atmosphere over the Hudson Bay region compared to the surrounding regions. On the annual light mixed layer wind speed pattern (Appendix A.II),

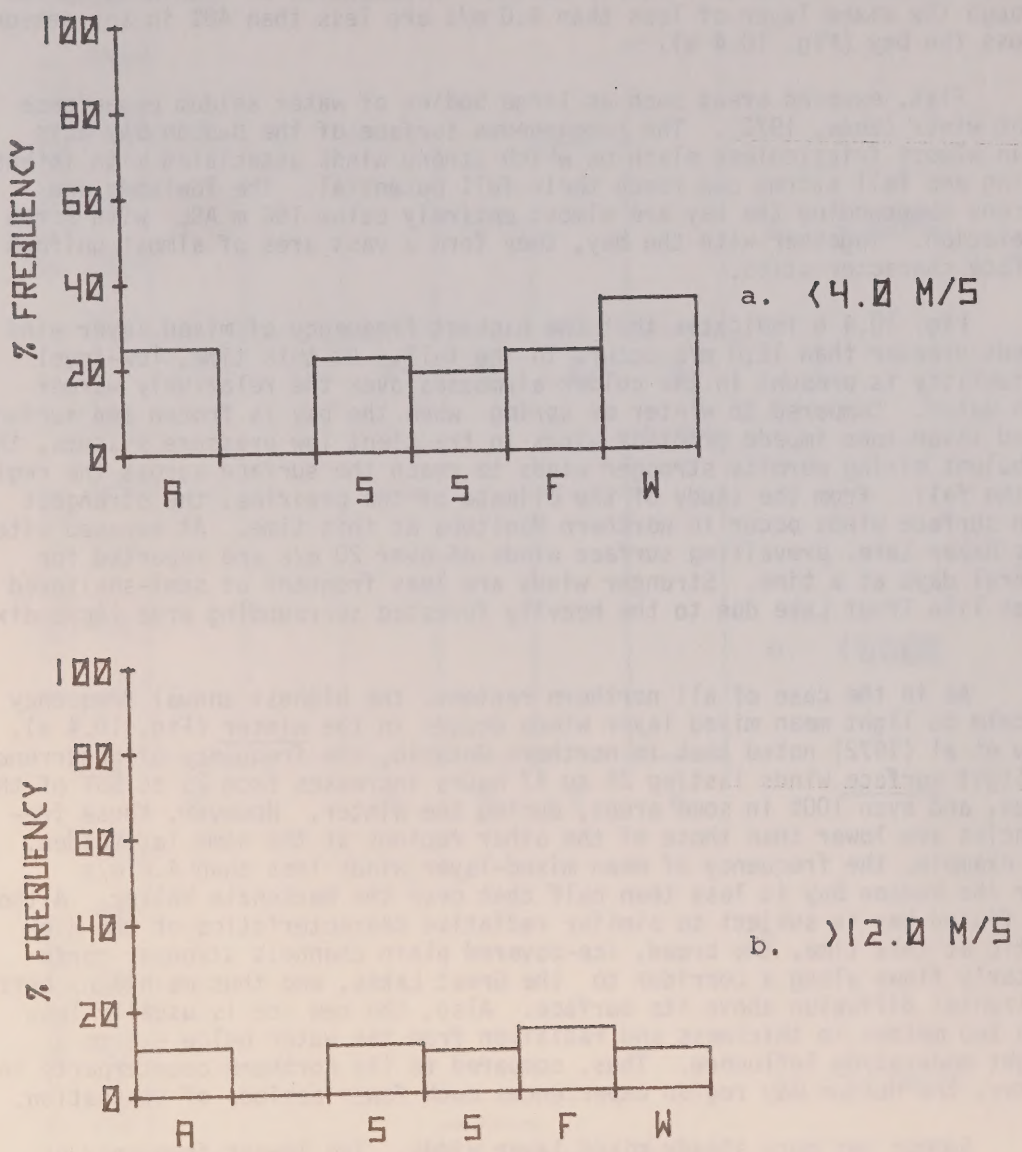


FIG. 10.4 Annual and Seasonal Frequencies of Occurrence of Mean Wind Speeds Through the Mixing Layer (m/s) for the Hudson Bay Region

for example, a 'ridge' of lower relative frequencies extends across the bay and northwestward towards Victoria Island. Frequencies of mean wind speeds through the mixed layer of less than 4.0 m/s are less than 40% in any season across the bay (Fig. 10.4 a).

Flat, exposed areas such as large bodies of water seldom experience light winds (Shaw, 1972). The homogeneous surface of the Hudson Bay acts as an almost frictionless plain on which strong winds associated with intense spring and fall storms can reach their full potential. The lowlands and barrens surrounding the bay are almost entirely below 150 m ASL with scrub vegetation. Together with the bay, they form a vast area of almost uniform surface characteristics.

Fig. 10.4 b indicates that the highest frequency of mixed layer wind speeds greater than 12.0 m/s occurs in the fall. At this time, low-level instability is present in the colder airmasses over the relatively warmer open water. Compared to winter or spring when the bay is frozen and surface-based inversions impede gradient winds in transient low pressure systems, this turbulent mixing permits stronger winds to reach the surface across the region in the fall. From the study of the climate of the prairies, the strongest mean surface winds occur in northern Manitoba at this time. At exposed sites like Baker Lake, prevailing surface winds of over 20 m/s are reported for several days at a time. Stronger winds are less frequent at semi-sheltered sites like Trout Lake due to the heavily forested surrounding area (Appendix D).

As in the case of all northern regions, the highest annual frequency of calm to light mean mixed layer winds occurs in the winter (Fig. 10.4 a). Shaw et al (1972) noted that in northern Ontario, the frequency of occurrence of light surface winds lasting 24 to 47 hours increases from 25 to 50% of the cases, and even 100% in some areas, during the winter. However, these frequencies are lower than those of the other regions at the same latitutdes. For example, the frequency of mean mixed-layer winds less than 4.0 m/s over the Hudson Bay is less than half that over the Mackenzie Valley. Although the frozen bay is subject to similar radiative characteristics of the High Arctic at this time, the broad, ice-covered plain channels stronger northwesterly flows along a corridor to the Great Lakes, and thus maintains better horizontal diffusion above its surface. Also, the new ice is usually less than two metres in thickness and radiation from the water below exerts a slight moderating influence. Thus, compared to its northern counterparts in winter, the Hudson Bay region experiences much fewer periods of stagnation.

Summer has more steady mixed layer winds. The lowest frequency of calms and the lowest frequency of strong winds occur at the same time (Fig. 10.4). In general, sea-breeze interactions and instability over the heated land areas provide constant motion in the boundary layer during the afternoon. Weak synoptic gradients at this time reduce periods of stronger flows.

10.4 MAXIMUM (AFTERNOON) VENTILATION COEFFICIENTS

Across the region, the higher frequency 'trough' of low mixing heights that extends from the Arctic Islands is counteracted by the lower frequency 'ridge' of light mean mixed layer winds. The net result is a weaker 'trough' of relatively high frequencies of ventilation coefficients less than 2000 m^2/s (Appendix A.III). Thus, in general, the Hudson Bay region has more frequent

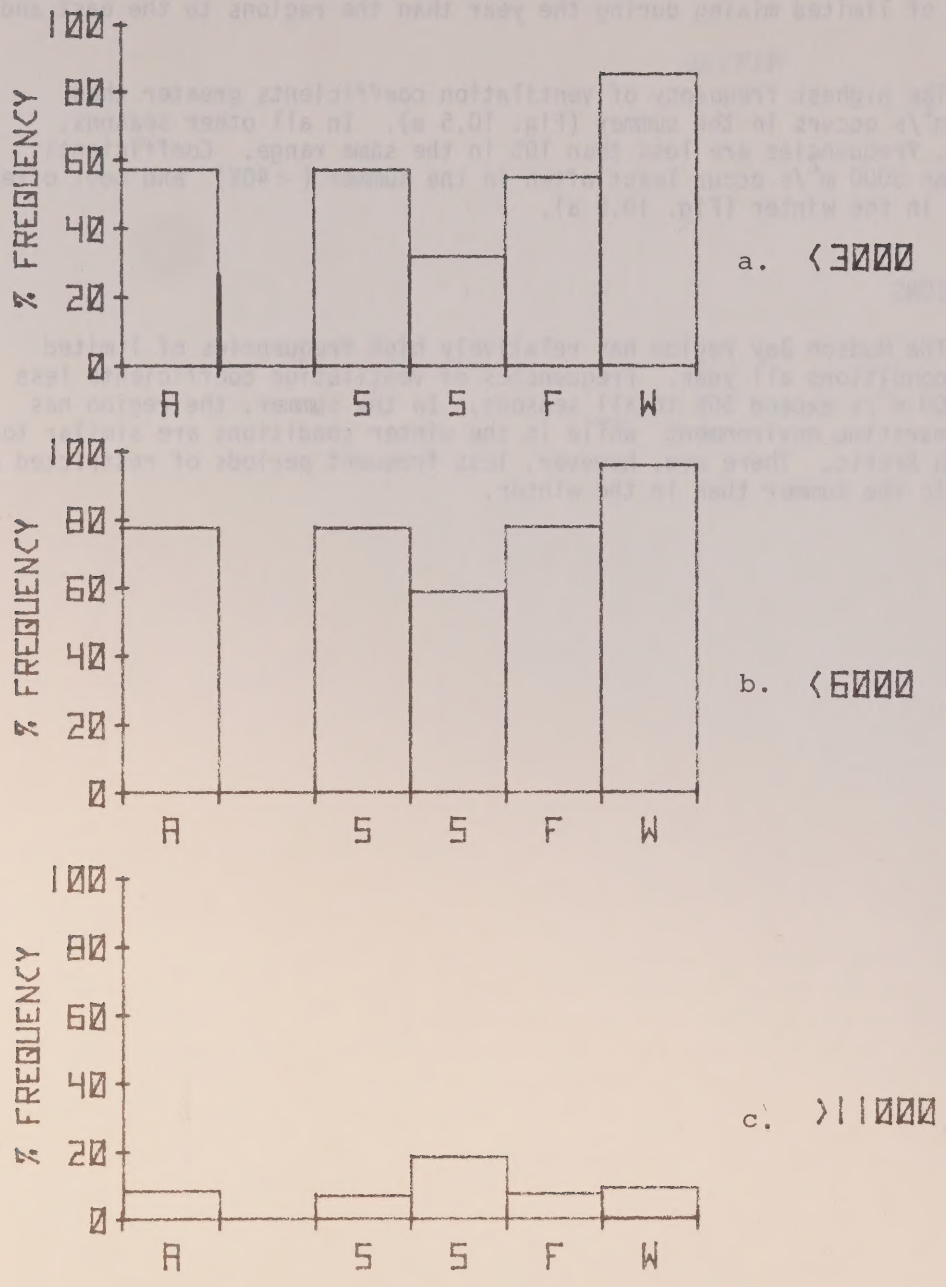


FIG. 10. 5 Annual and Seasonal Frequencies of Occurrence of Afternoon Ventilation Coefficients (m^2/s) for the Hudson Bay Region

periods of limited mixing during the year than the regions to the east and west.

The highest frequency of ventilation coefficients greater than 11,000 m^2/s occurs in the summer (Fig. 10.5 a). In all other seasons, however, frequencies are less than 10% in the same range. Coefficients less than 3000 m^2/s occur least often in the summer (< 40%) and most often (> 85%) in the winter (Fig. 10.5 a).

10.5 CONCLUSIONS

The Hudson Bay region has relatively high frequencies of limited mixing conditions all year. Frequencies of ventilation coefficients less than 6000 m^2/s exceed 50% in all seasons. In the summer, the region has a cold maritime environment while in the winter conditions are similar to the High Arctic. There are, however, less frequent periods of restricted diffusion in the summer than in the winter.

BAFFIN

CHAPTER 11

CHAPTER 11

BAFFIN REGION

11.1 INTRODUCTION

For the purposes of this regional study of mixing depth parameters, the Baffin region has been separated from the remainder of the Arctic Archipelago (Fig. 11.1). Climatic studies identify the eastern Baffin Island and Hudson Strait areas as a modified maritime Arctic environment. A reflection of the Gulf Stream current penetrates into Davis Strait and modifies areas surrounding the open waters during the fall and winter. Similarily, the milder airmasses are carried northward by east coast storms that travel along the Atlantic coast and Labrador Sea, and frequently come to rest in Baffin Bay.

A mountainous ridge covered with glacial ice extends along the western boundary of the region. This glacial ridge has the highest elevations in the Arctic Archipelago with peaks from 1000 to 3000 m extending from Ellesmere Island. The coastal range in the southern sections confines maritime airmasses to the narrow coastline and protects the same area from the very cold airmass to the west.

Upper-air stations in the region include: Clyde, Frobisher Bay, and Fort Chimo (Appendix D). Clyde and Frobisher Bay are located on the east coast of the Baffin Island, east of the main range, and represent the milder Arctic environment. Fort Chimo is located further south on Ungava Bay and reflects a similar maritime influence.

11.2 MAXIMUM AFTERNOON MIXING HEIGHTS

11.2.1 General Characteristics

Annually, over 70% of the mixing heights are concentrated in the lowest 600 m (Fig. 11.3 b). In the summer, less than 50% occur in this range, while in the winter over 97% of the cases have mixing heights below 600 m. Frequencies of mixing heights above 2000 m are virtually negligible in all seasons (Fig. 11.3 c). In fact, frequencies of mixing heights greater than 1000 m are small at any time (Fig. 11.2).

On the annual frequency pattern (Appendix A.I) a 'ridge' of slightly lower frequencies of low mixing heights extends across the region into Baffin Bay. (A higher frequency 'trough' extends across the High Arctic Islands and the Hudson Bay). This general pattern is clearly visible on the corresponding fall, winter and spring frequency charts.

11.2.2 Winter Conditions

The lower frequency 'ridge' that extends through the region on the low mixing height charts reflects (i) the modifying influence of the milder maritime environment, (ii) the influx of milder airmasses, and (iii) the

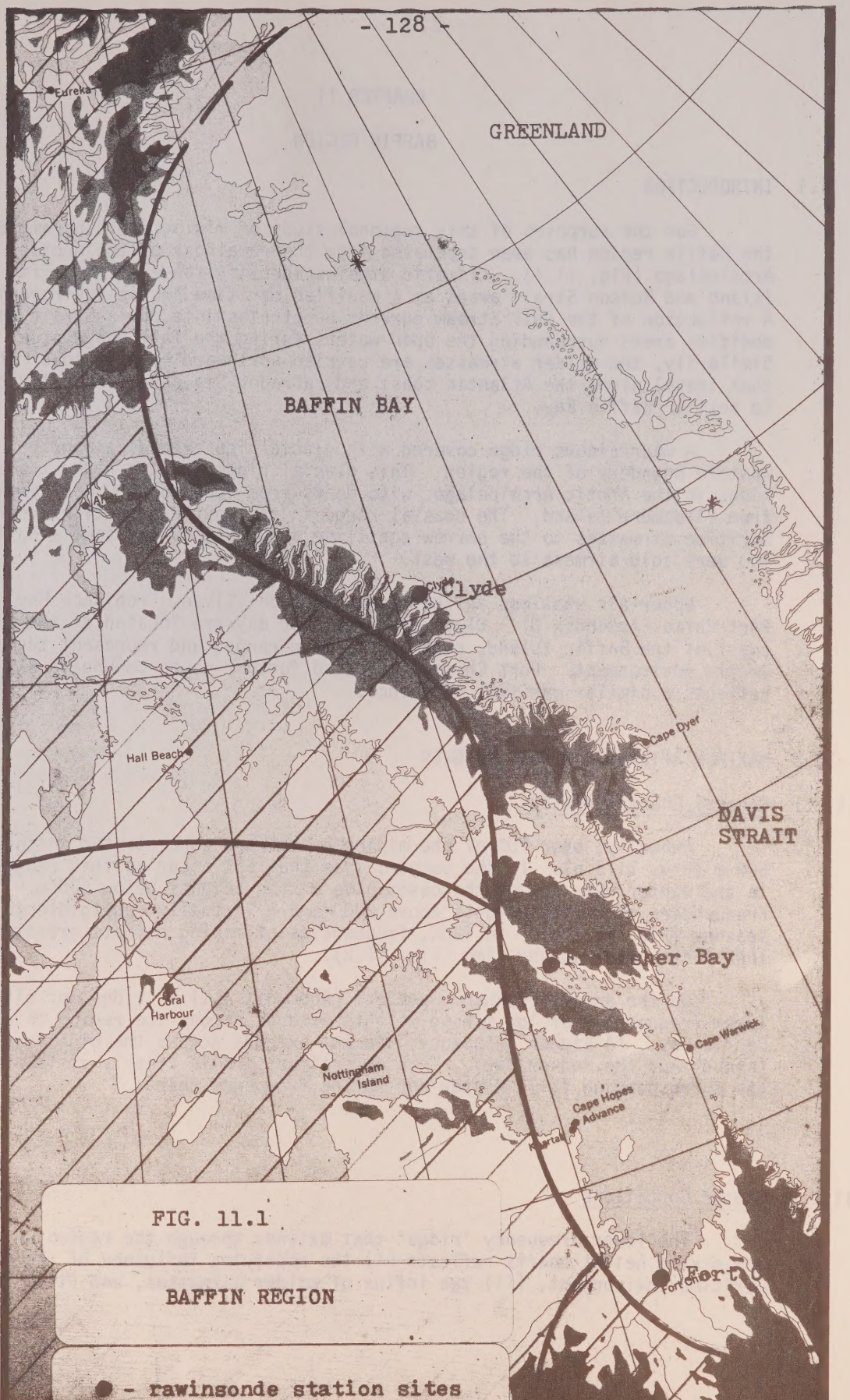


FIG. 11.1

BAFFIN REGION

● - rawinsonde station sites

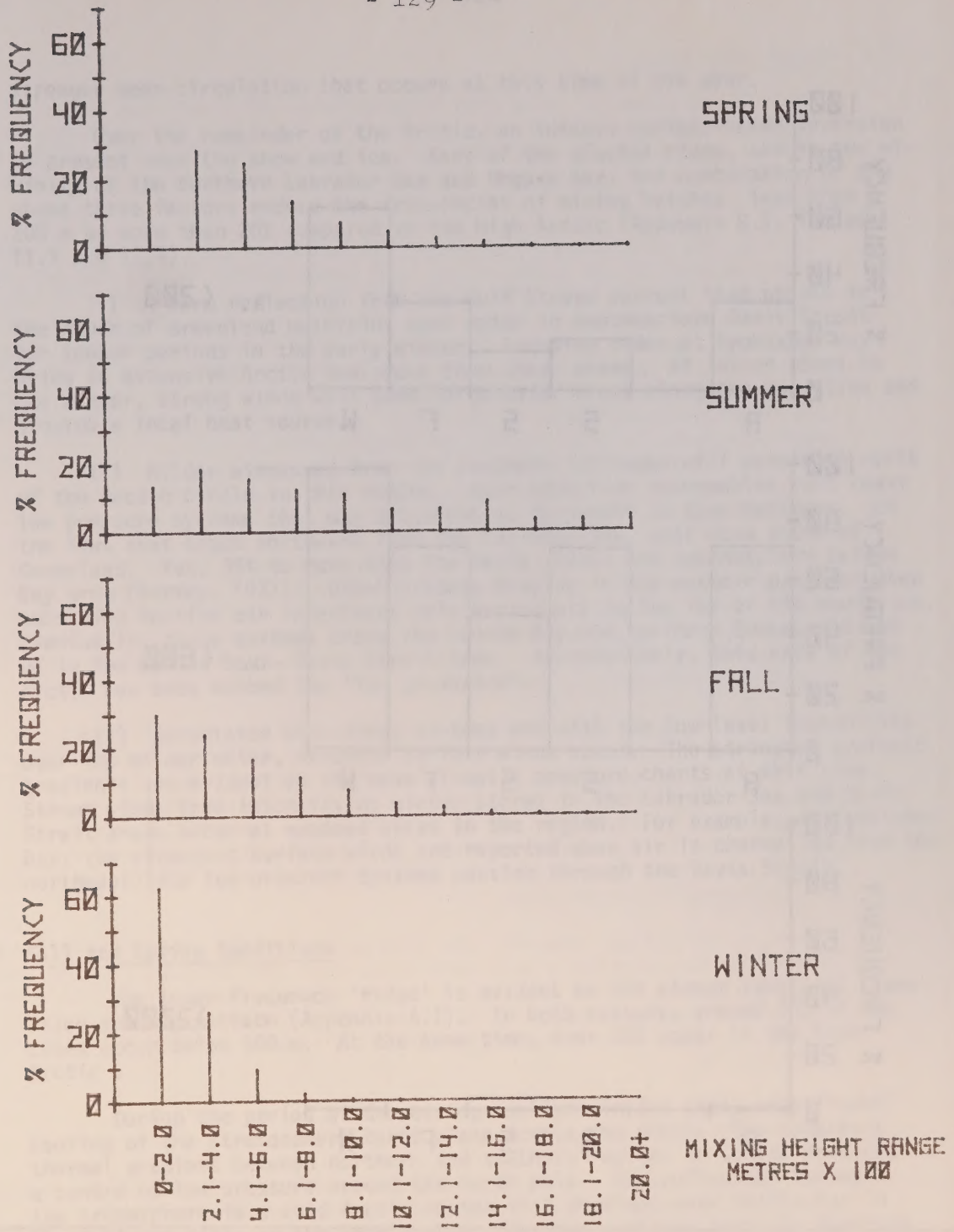


FIG. 11.2 SEASONAL FREQUENCY HISTOGRAMS OF SPECIFIED MAXIMUM MIXING HEIGHTS
REGION: BAFFIN

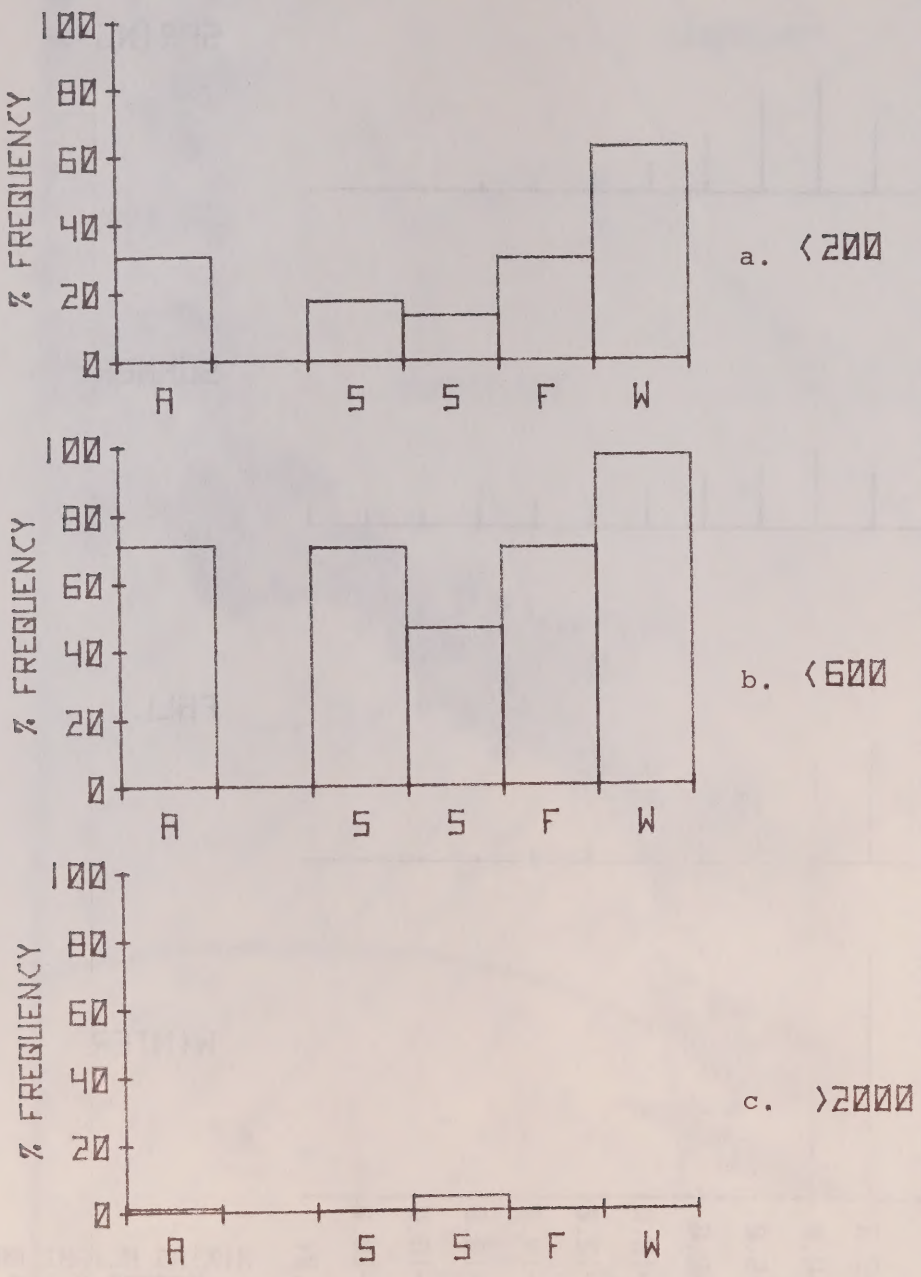


FIG. 11.3 Annual and Seasonal Frequencies of Occurrence of Maximum (Afternoon) Mixing Heights (m) for the Baffin Region

stronger mean circulation that occurs at this time of the year.

Over the remainder of the Arctic, an intense surface-based inversion is present over the snow and ice. East of the glacial ridge, and in the vicinity of the northern Labrador Sea and Ungava Bay, the combination of the above three factors reduce the frequencies of mixing heights less than 200 m by more than 20% compared to the High Arctic (Appendix B.I, Tables 11.1 and 12.1).

i) A warm reflection from the Gulf Stream current that passes to the south of Greenland maintains open water in southeastern Davis Strait for longer periods in the early winter. Incoming tides at Frobisher Bay bring in extensive Arctic sea smoke from these areas. At other times in the winter, strong winds will open large water areas along the coastline and provide a local heat source.

ii) Milder airmasses from the southern latitudes will penetrate north of the Arctic Circle in this region. Warm advection accompanies east coast low pressure systems that may originate as far south as Cape Hatteras. Of the lows that track northward from the Labrador Sea, most move south of Greenland. Yet, 35% do move into the Davis Strait and southeastern Baffin Bay area (Bursey, 1977). Other systems develop in the western prairies when subsiding Pacific air interfaces cold Arctic air to the lee of the mountains. Eventually, these systems cross the Hudson Bay and northern Quebec and end up in the Baffin Bay - Davis Strait area. Appropriately, this area of the Arctic has been dubbed the "low graveyard".

iii) Associated with these systems and with the low-level instability over the milder water, stronger surface winds occur. The strongest cyclonic gradients are evident on the mean climatic pressure charts at this time. Strong winds from intensifying winter storms in the Labrador Sea and Davis Strait areas occur at exposed sites in the region. For example, at Frobisher Bay, the strongest surface winds are reported when air is channelled from the northwest into low pressure systems passing through the Davis Strait.

11.2.3 Fall and Spring Conditions

The lower frequency 'ridge' is evident on the almost identical transition seasons pattern (Appendix A.I). In both seasons, around 70% of the cases occur below 600 m. At the same time, over 93% occur in the High Arctic .

During the period of decreasing sunlight in the fall, significant cooling of the stratosphere takes place across the north. The resultant thermal gradient between northern and southern regions in Canada produces a centre of low pressure around the north pole. The reflection through the troposphere is a cold Arctic vortex that develops over Baffin Bay in the fall and fills in the late spring. Maximum cyclonic activity develops at the interface of the relatively warmer water and dome of cold Arctic air over the land or continuous ice-fields. This net circulation diffuses the lowest layers of the atmosphere and limits the periods of long-term stagnation such as that found further west of the region over the High Arctic Islands.

11.2.4 Summer Conditions

The frequencies of mixing heights below 600 m are the lowest of the annual averages during this season (Fig. 11.3 b). The patterns in Appendix A.I, however, show that this is an area of relatively higher frequencies of low mixing heights with respect to the continental regions to the south.

On the east coast of Labrador and Baffin Island, the cold Labrador current maintains ice in the inlets and inner coastal waters for most of the summer. In addition, ice frequently flows along the Hudson Strait from the Foxe Basin reservoir. Very high tides* carry cold surface water from the currents to the shores. This cold surface topped by very warm summertime airmasses produces a stable layer above the water. (North of the Arctic Circle, 24-hours of sunlight compensate for the low sun-angle and considerable airmass warming results.) Advection inland of this stable layer suppresses mixing heights at coastal sites.

11.3 MEAN WIND SPEEDS THROUGH THE MIXING LAYER

On the annual and seasonal frequency patterns (Appendix A.II) a 'trough' of relatively high frequencies of mean winds less than 4.0 m/s extends from Ellesmere Island to Baffin Bay and southern Baffin Island. Paradoxically, during the winter mean mixed layer winds greater than 12.0 m/s occur with twice as much frequency over the Baffin region as over the High Arctic (Appendix C, Part 2).

The 'trough' pattern described above reflects conditions at the relatively protected sites on Ellesmere Island and Baffin Island (see Appendix D). The maximum geostrophic pressure gradient occurs in a cyclonic flow across the High Arctic Islands between the cold Arctic vortex in the east and the ridge in the west. On an annual basis, protected sites along the glacial ridge in the east experience less horizontal mixing at lower levels in the atmosphere compared to the more exposed locations over the fairly uniform terrain further west.

In the winter, however, the cold dome over the Arctic Islands to the west maintains relatively calm conditions near the surface. At the same time, the Baffin region has more frequent storms tracking into its area of influence. Unstable boundary layer conditions allow greater mixing and as a result, strong mean winds occur periodically even at the protected sites in the region.

11.4 MAXIMUM AFTERNOON VENTILATION COEFFICIENTS

On the annual frequency charts of ventilation coefficients less than 1000 m^2/s (Appendix A.III) the pattern across the Baffin region reflects the 'trough' on the calm to light mixed layer wind speed frequency charts rather than the 'ridge' of relatively lower frequencies on the low mixing height charts. Furthermore, from Fig. 11.5 b the ventilation coefficients

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* NOTE: Frobisher Bay area has some of the highest tides in the world.

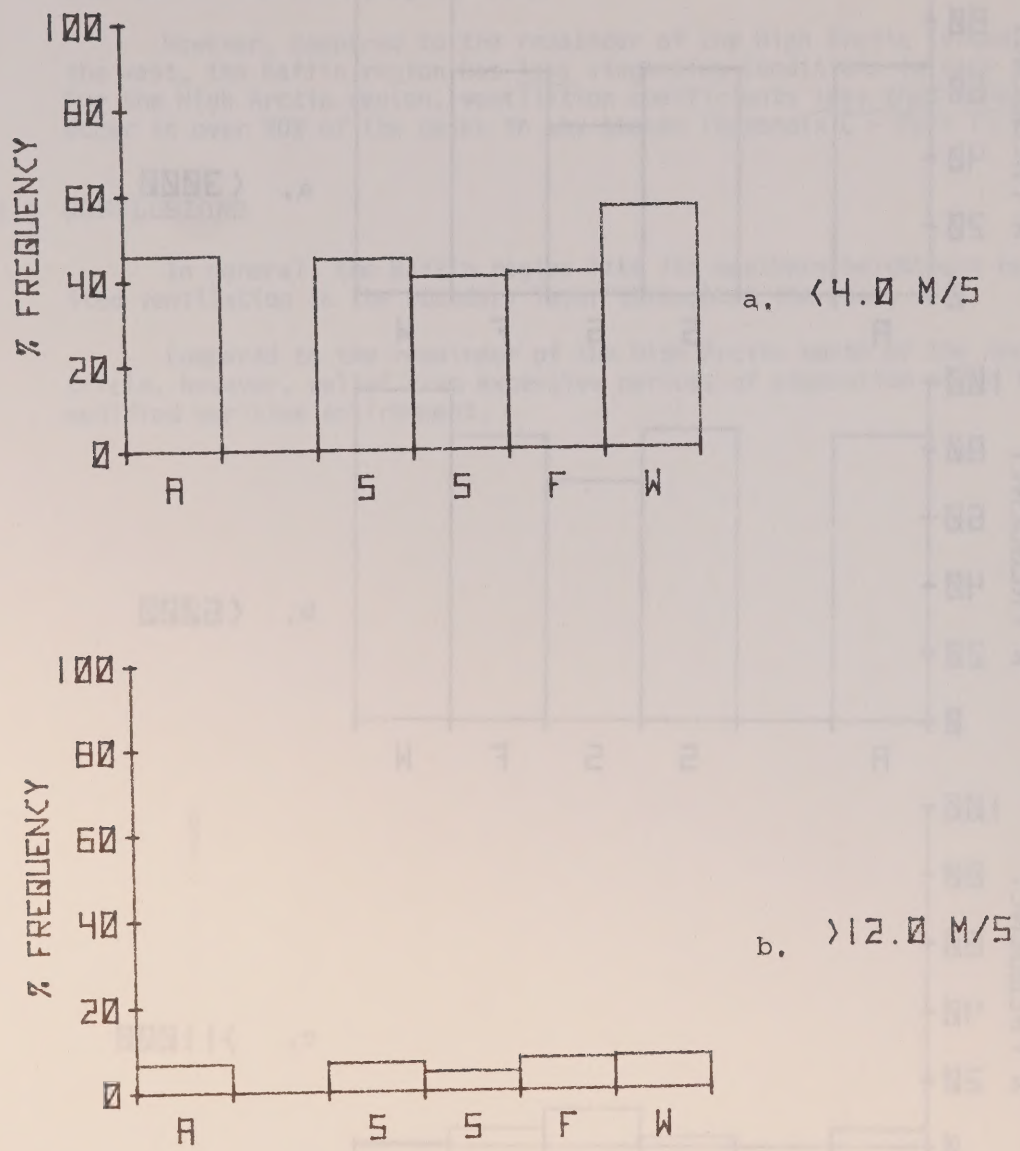

FIG. 11.4 Annual and Seasonal Frequencies of Occurrence of Mean Wind Speeds Through the Mixing Layer (m/s) for the Baffin Region

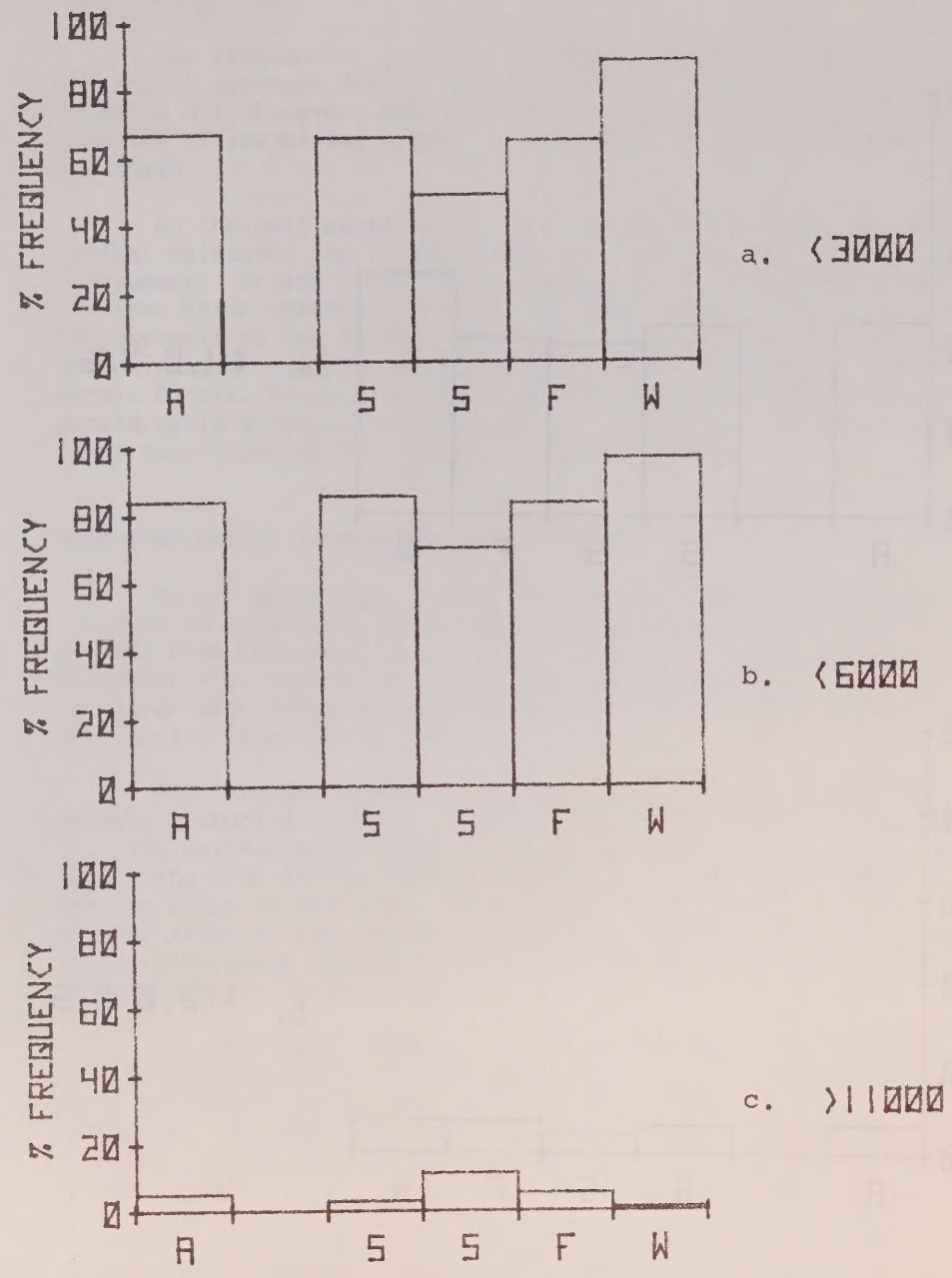

FIG. 11.5 Annual and Seasonal Frequencies of Occurrence of Afternoon Ventilation Coefficients (m^2/s) for the Baffin Region

less than 6000 m^2/s occur in over 70% of the cases in any season. Only in the summer do ventilation coefficients greater than 11,000 m^2/s occur over 10% of the time (Fig. 11.5 c).

However, compared to the remainder of the High Arctic Islands to the west, the Baffin region has less stagnating conditions in each season. For the High Arctic region, ventilation coefficients less than 6000 m^2/s occur in over 90% of the cases in any season (Appendix C - Part 1).

11.5 CONCLUSIONS

In general, the Baffin region like its northern neighbours has limited ventilation in the boundary layer throughout the year.

Compared to the remainder of the High Arctic north of the Arctic Circle, however, relief from excessive periods of stagnation occur in this modified maritime environment.

HIGH ARCTIC

CHAPTER 12

CHAPTER 12

HIGH ARCTIC REGION

12.1 INTRODUCTION

The northern regions in this study consitute a vast section of Canada, over one-third of the total geographical area. A large part of this is the Arctic Archipelago (the High Arctic and Baffin regions) and consists of mainly ice and snow covered islands north of the Arctic Circle.

The High Arctic has the following inherent characteristics that determine atmospheric diffusion properties in the region.

1. Latitude: The High Arctic Islands span an area mainly north of latitude 70°N. North of the Arctic Circle the sun does not set in mid-summer nor rise in mid-winter. The extreme length of the Polar Night in the winter and of the day in summer ("Land of the Mid-Night Sun") is the major factor in climate control at higher latitudes.

2. Surface Cover: A continuous and highly reflective snow and ice cover is present most of the year. The remainder of the year, the vast water and ice surfaces combined with a low sun-angle also has high reflectivity.

3. Mean Circulation: The cold Arctic vortex in the eastern Arctic is present on the mean pressure charts with varying degrees of intensity all year long. Between this mean synoptic feature in the east and the Arctic high pressure ridge in the west, a net northwesterly cyclonic flow extends over the islands.

4. Topography: The region consists of a series of islands of relatively uniform elevation bounded by the vast Arctic Ocean on the west and a high mountain range, Baffin Bay, and northern Greenland to the east.

A reasonably dense network of rawinsonde stations representative of conditions* in this area extends across the region (Fig. 12.1). These stations include: Alert, Eureka, Isachsen, Mould Bay, Resolute Bay, Sachs Harbour, Coppermine and Hall Beach. The most northerly of these stations is Alert on Ellesmere Island and is less than 8 degrees south of the Pole. A complete description of the sites of these upper-air stations is given in Appendix D.

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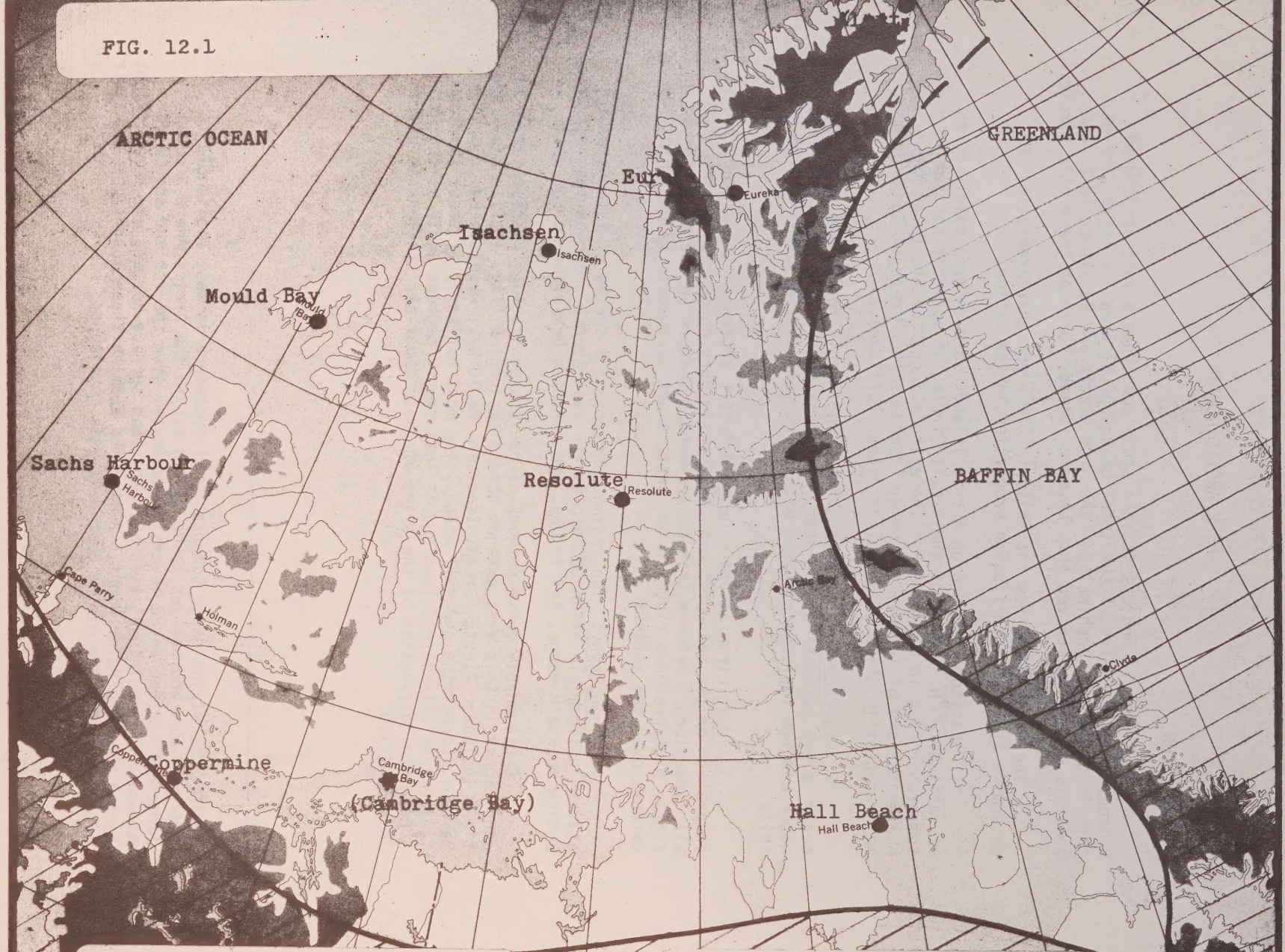
* NOTE: The mixing depth computational procedure is most applicable to mid-latitudes and has yet to be tested out in the Arctic where a quasi-permanent surface-based inversion dominates over the ice and snow cover. Moreover, dirunal insolation and resultant surface-heating are non-existent during the long Polar Night. A study to examine these conditions and their relationship to the mixing depth analysis is planned.

FIG. 12.1



● - rawinsonde station sites

HIGH ARCTIC REGION

12.2 MAXIMUM AFTERNOON MIXING HEIGHTS

12.2.1 General Characteristics

The most notable feature on the seasonal mixing height frequency histogram (Fig. 12.2) is the negligible frequencies above 1000 m in all seasons. Moreover, the highest annual concentrations occur in the lowest 200 m above ground level. On a seasonal basis, each mixing height level above 600 m occurs less than 10% of the time (Appendix B, Table 12.1). Within the limits of the data, the above statistics imply that the High Arctic has very low vertical dispersion most of the time.

In the lowest 400 m, the annual mixing height frequency pattern (Appendix A.I) shows a high frequency 'trough' extending across the islands from Alert to the northern part of Victoria Island. A secondary axis extends southeastward to Hudson Bay. This general pattern is consistent with the mean annual temperature pattern of the High Arctic Islands. The axis of lowest mean temperatures corresponds to the 'trough' of high frequencies of low mixing heights. Also, the mean annual maximum mixing height pattern across the Arctic Islands (Portelli, 1977) has a similar dual trough pattern. The mean values range from 200 m in the far north to between 300 to 400 m across the south.

12.2.2 Winter Conditions

The most frequent mixing heights below 200 m (over 80%) occur in this season (Fig. 12.3 a). Of all the regions across Canada, this represents the highest frequency in this mixing height range (Appendix C - Part 2, Table 4). In addition, winter has the highest frequency of mixing heights below 600 m although variations in this range from season to season is small (Fig. 12.3 b).

The above frequency of critically low mixing heights are a consequence of the severely limited radiant energy available to the region during the winter months. Due to the lack of incoming solar radiation at mid-winter, variations in the low-level temperature profile are due to long-wave radiation from below (i.e., radiational cooling or conversely, warm advection from a local heat source). Most of the time during the darkness and mainly clear skies of the Arctic winter, radiational cooling above the snow and ice surface is a maximum. Very low surface temperatures and pronounced surface-based inversions persist for long periods. Maxwell (1978) has prepared a detailed report on the formation and structure of the semi-permanent temperature inversion in the Arctic.

The snow cover extends over all of the islands by the end of October and remains intact until the end of May. Except for open leads along the coastal areas, sea-ice covers all of the Arctic Ocean, Baffin Bay and Foxe Basin throughout the winter. At Resolute Bay, the channels are frozen from November to April in most years.

Locally, the impact of the intense Arctic inversion may be interrupted by the advection of heat and moisture from (i) low pressure systems, or (ii) open leads and large tidal cracks.

(i) In the winter, the usually slow-moving storms prefer paths

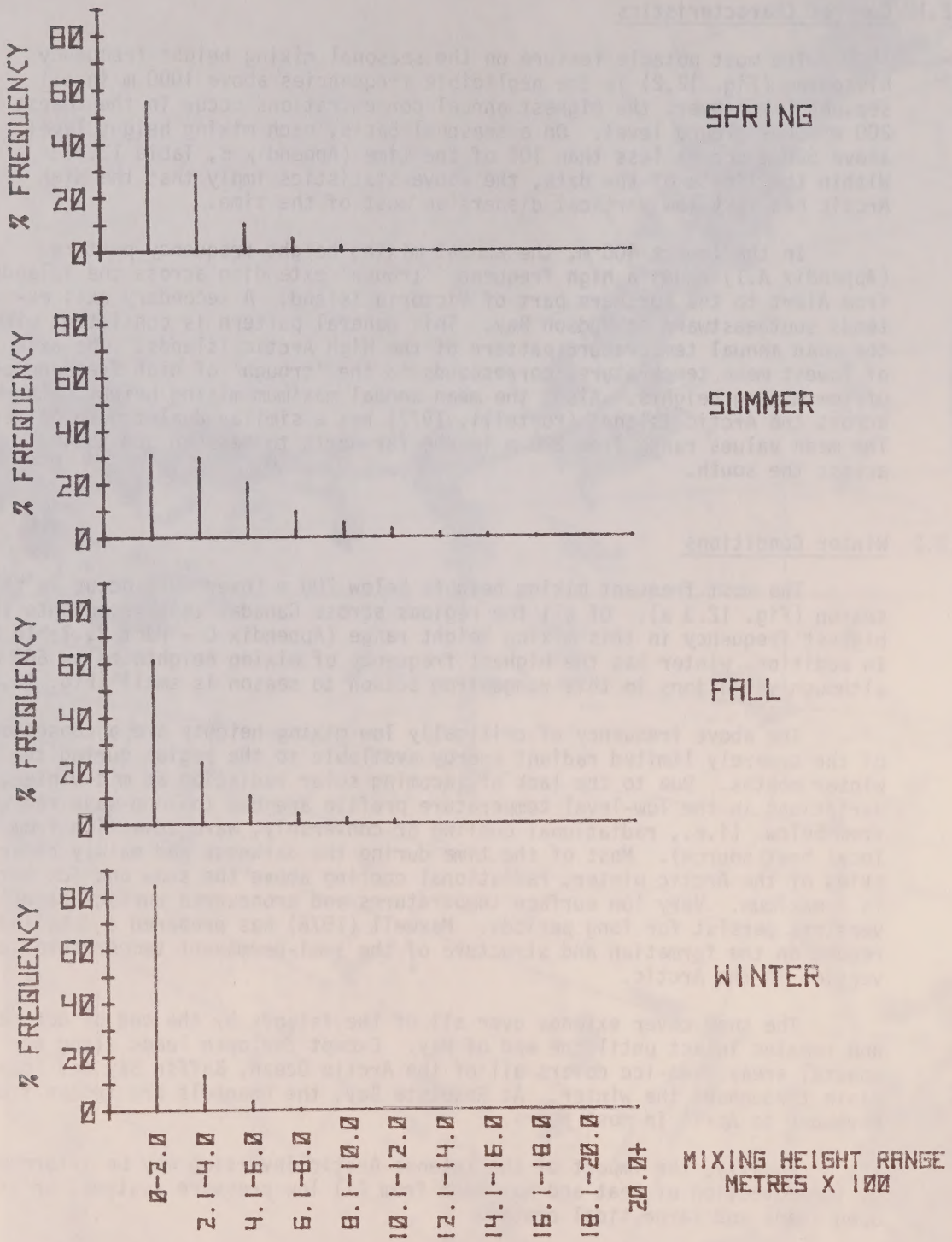


FIG. 12.2 SEASONAL FREQUENCY HISTOGRAMS OF SPECIFIED MAXIMUM MIXING HEIGHTS

Region: High Arctic

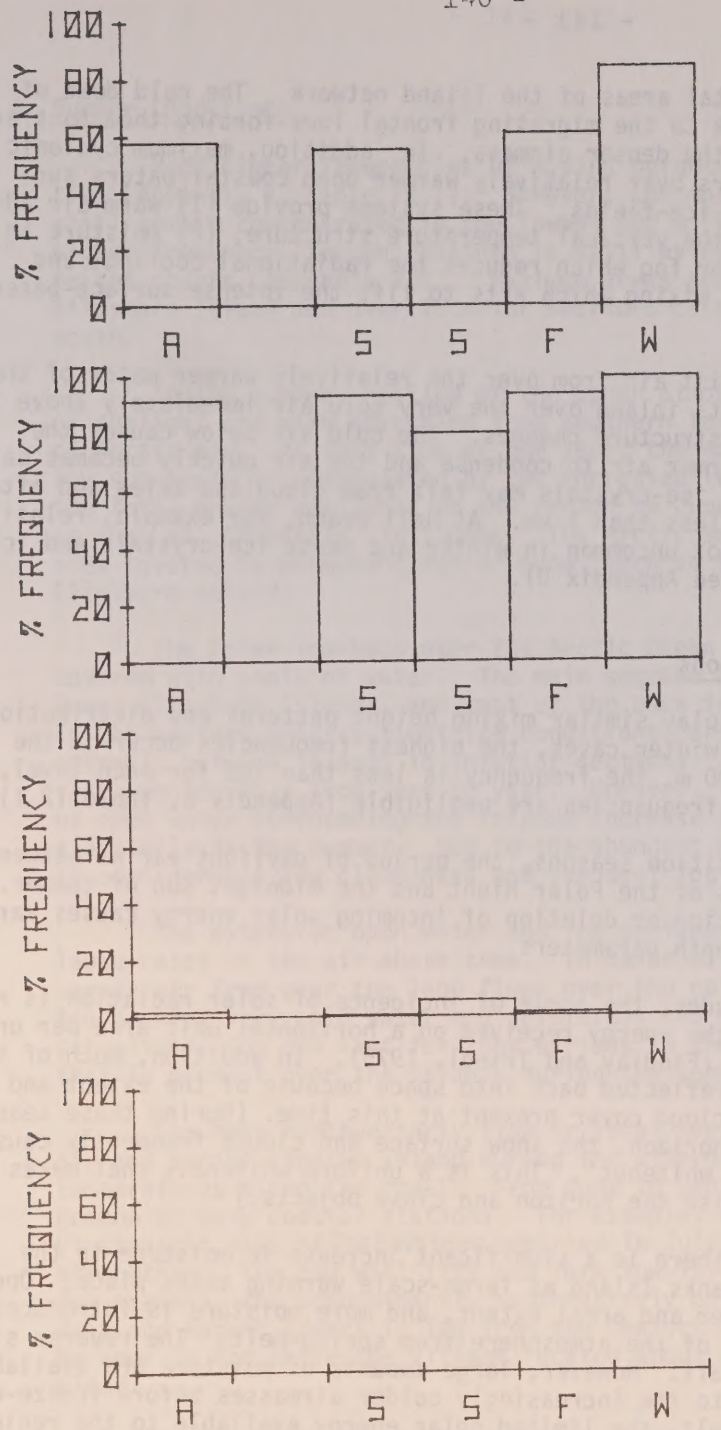


FIG. 12.3 Annual and Seasonal Frequencies of Occurrence of Maximum (Afternoon) Mixing Heights (m) for the High Arctic Region

along the southern coastal areas of the island network. The cold dome of Arctic air forms a block to the migrating frontal lows forcing them to travel along the periphery of the denser airmass. In addition, maximum cyclonic activity normally occurs over relatively warmer open coastal waters surrounded by cold land or ice-fields. These systems provide (1) warm air advection which modifies the vertical temperature structure, (2) moisture in the form of low clouds or fog which reduces the radiational cooling, and (3) low-level turbulent mixing which acts to lift the intense surface-based inversions.

(ii) When the moist air from over the relatively warmer water of the nearby open leads advects inland over the very cold air immediately above the surface, the inversion structure changes. The cold air below causes the water vapour in the warmer air to condense and the air quickly becomes saturated. In such cases, ice-crystals may fall from cloudless skies and often reduce visibilities to less than 1 km. At Hall Beach, for example, relative humidities of 82% are not uncommon in winter and dense ice-crystals and ice-fog occur frequently (see Appendix D).

12.2.3 Spring and Fall Conditions

Both seasons display similar mixing height patterns and distributions (Fig. 12.2). Like the winter cases, the highest frequencies occur in the lowest 200 m. Above 400 m, the frequency is less than 10% for each level, while above 800 m, the frequencies are negligible (Appendix B, Table 12.1).

During the transition seasons, the period of daylight varies between the continuous darkness of the Polar Night and the midnight sun of summer. The corresponding addition or deletion of incoming solar energy causes variations in the mixing depth parameters.

At higher latitudes, the angle of incidence of solar radiation is relatively small. Thus, the energy received on a horizontal unit area per unit time is likewise small (Findlay and Triedl, 1975). In addition, much of the incident radiation is reflected back into space because of the extent and duration of snow, ice and cloud cover present at this time. (During these seasons, with the sun near the horizon, the snow surface and clouds frequently cause what is known as an 'Arctic whiteout'. This is a uniform whiteness that makes it difficult to distinguish the horizon and close objects.)

In the spring, there is a significant increase in moisture in the coastal areas around Banks Island as large-scale warming takes place. Open leads increase in number and areal extent, and more moisture is introduced into the lowest layers of the atmosphere from spring-melt. The reverse situation occurs in the fall. However, large amounts of moisture are available through evaporation into the increasingly colder airmasses before freeze-over is complete. As a result, the limited solar energy available to the region during the Arctic twilight is further reduced. A net depletion occurs. Mean surface temperatures and maximum mixing heights are correspondingly lower across the north compared to the regions to the south.

12.2.4 Summer Conditions

Much higher frequencies of mixing heights above 600 m occur at this time (Appendix B, Table 12.1). However, the most frequent mixing heights still remain concentrated in the lowest 600 m (Fig. 12.2). The relatively higher frequency 'trough' pattern is still evident on the lowest mixing height charts (Appendix A.I). Maximum areas are confined to extreme northern Ellesmere Island and over interior sections of the island network across the south.

In the summer, heating of the upper atmosphere due to the long periods of sunlight and warm advection from southern latitudes inhibits the build-up of Arctic air. At this time of the year, the energy attenuation due to the low sun-angle is compensated by the increased length of day. As a result, the total energy available to the region in June and July is about the same as that at temperate latitudes. The Arctic source region reduces to an area covered by permanent ice or snow, such as the glacial ridge along Ellesmere Island.

The Polar ice-pack over the Arctic Ocean is partially broken and covered with pools of water. The main segment has moved off the coast of the Queen Elizabeth Islands, and most of the pack is clear of the Beaufort Sea. In the eastern Arctic, light ice conditions persist except for a few closed channels between islands in interior sections. The mean ice conditions may vary considerably from year to year. However, in most cases, numerous bodies of open water surrounding the islands increase the relative humidity substantially in the summer. Due to the abundant moisture now available, there is considerable low cloudiness and frequent fog over the entire region.

The extensive open water and ice surfaces maintain relatively stable lapse rates in the air above them. In cases of an offshore gradient flow, warmer air from over the land flows over the cold surface of the residual ice-pack or very cold water and reinforces the stable structure. In these situations, fog can last for long periods in the weak synoptic circulation that is present over the islands during the summer.

The mean northwesterly flow or local sea-breezes will advect colder air and marine stratum inland during the afternoon and reduce maximum surface temperatures along the coast. From June to September, advection fog is common at many coastal stations. For example, at Resolute Bay as many as 21 straight days of fog have been reported in July. Frequently, as the wind strengthens, the fog will lift and form low-lying stratus. At Sachs Harbour for example, the predominantly southeasterly onshore flows that occur in July and August advect in fog from the Beafort Sea. The observing site will be down in fog while the village located about 80 m lower will have low-lying cloud.

Thus, along the coast, sunshine is significantly reduced. This net loss of heat energy results in lower maximum surface temperatures and correspondingly lower afternoon mixing heights at coastal locations compared to that further inland. The cold maritime air that results from a recent trajectory over the water or ice surface normally modifies as it penetrates inland. The exposed rock surface or dried tundra vegetation (lichen) extensive over the islands at this time absorbs more incoming radiation during the 24-hour solar day. This results in more frequent low-level convection and

vertical currents through the boundary layer.

In summary, the greatest vertical mixing occurs during this season. However, compared to the other regions of Canada, high mixing heights occur least often. In addition, there is considerable variation in the mixing heights from location to location within the region. Munn et al (1970) noted that the northern and eastern Arctic are characterized by considerable variability in the frequency of surface-based inversions in the summertime. These variations are due to the large thermal and physical spatial contrasts present over the cold water or ice surfaces and the heated rock and tundra.

12.3 MEAN WIND SPEED THROUGH THE MIXING LAYER

12.3.1 General Characteristics

The highest annual frequency occurs in the calm to light mixed layer wind speed range (Appendix B, Table 12.2). The seasonal distributions (Fig. 12.4 a) indicate that the maximum frequency of these light winds occurs in the winter and spring, and a minimum occurs in the summer. In the latter season, the mean winds favour the 4.1 to 8.0 m/s range. The strongest mean winds (i.e., greater than 12.0 m/s) occur most often in the fall, closely followed by spring (Fig. 12.4 b). Both the summer and winter frequencies in this category are less than 5%.

The calm to light mixed-layer wind speed frequency patterns (Appendix A.II) show a relatively lower frequency 'ridge' extending northward from western Hudson Bay to Victoria Island and Banks Island, and into the Arctic Ocean. An annual maximum of stagnating conditions occurs over northern Ellesmere Island where over 70% of the cases have mean wind speeds less than 4.0 m/s through the lowest layers above the surface.

The mean pressure pattern in the eastern Arctic is characterized by the cold Arctic vortex. In the western Arctic, a semi-permanent ridge extends from the Arctic Ocean southward. Between the low and trough system in the east and the anticyclonic circulation in the west, a net moderate to strong northwesterly gradient extends across the region. The existence of the strong surface-based inversion over most of the region from fall to spring, and over ice-covered areas in the summer, however, inhibits the full potential of the gradient near the surface. Periodically, intense systems will break through this surface layer and raise the mean wind speeds. These major systems are generally infrequent across the Arctic throughout the year. Secondary storm tracks occur in February and August, and are usually found along the southern reaches of the island network. These factors limit the general movement of air at lower levels across the region on an annual basis.

Other factors complicate the low-level wind statistics. For example, sheltered locations will not respond to the full impact of the synoptic flow over the region while exposed sites may reflect anomalously high values of wind speeds caused by mesoscale effects. Many settlements and reporting stations in the north are located in protected areas and as a result, wind measurements are usually light. Eureka and Clyde, for example, have the longest periods of calm surface winds according to the climatic records. Similarily, the highest frequency of calm to light mean wind speeds

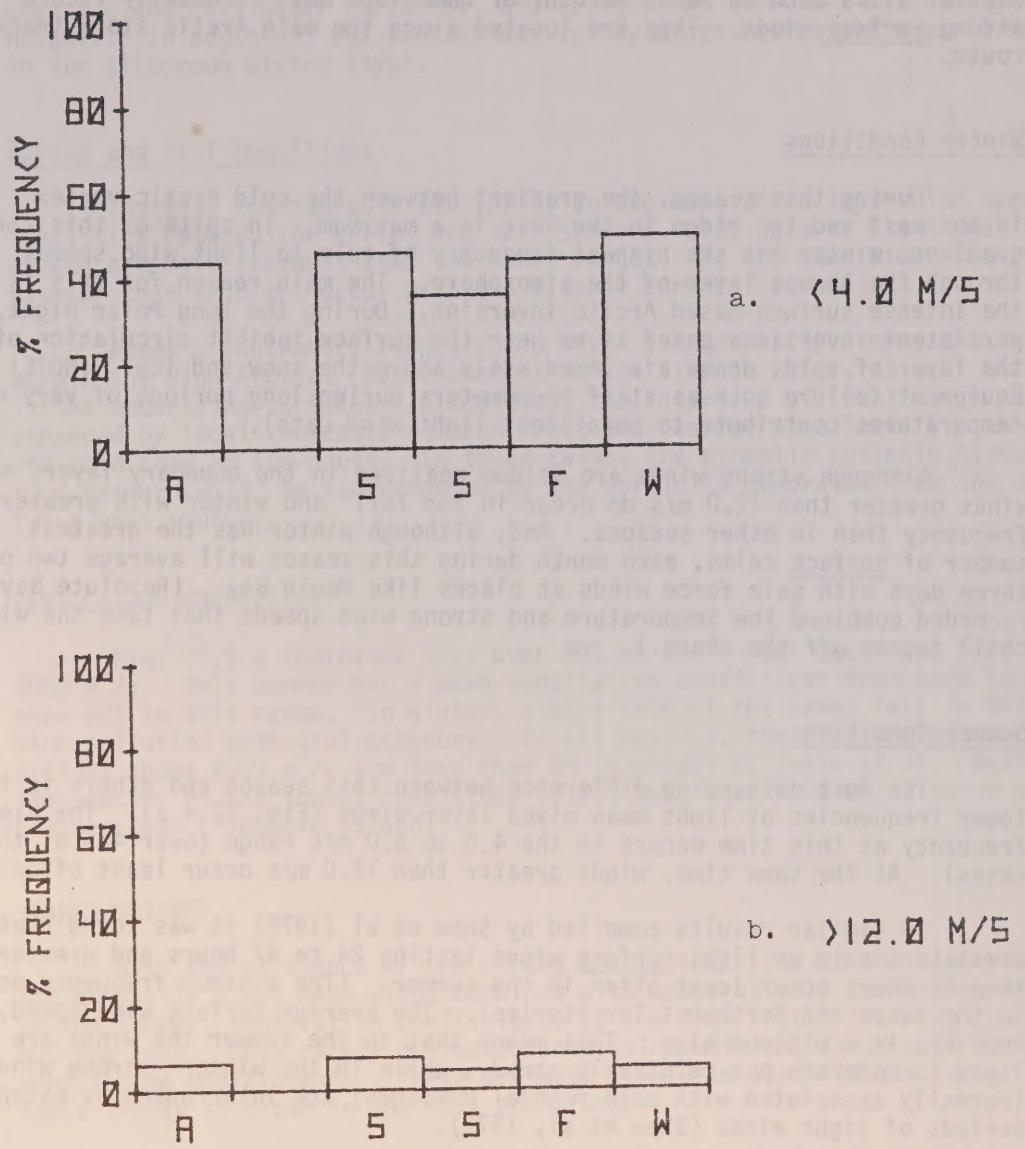


FIG. 12.4 Annual and Seasonal Frequencies of Occurrence of Mean Wind Speeds Through the Mixing Layer (m/s) for the High Arctic Region

through the mixed layer occurs at Eureka. On the other hand, exposed coastal sites such as Sachs Harbour or Cambridge Bay* frequently record strong surface winds. They are located along the main Arctic storm track route.

12.3.2 Winter Conditions

During this season, the gradient between the cold Arctic vortex in the east and the ridge in the west is a maximum. In spite of this strong gradient, winter has the highest frequency of calm to light wind speeds through the lowest layer of the atmosphere. The main reason for this is the intense surface-based Arctic inversion. During the long Polar night, persistent inversions based at or near the surface inhibit circulation of the layer of cold, dense air immediately above the snow and ice. (NOTE: Equipment failure such as stiff anemometers during long periods of very cold temperatures contribute to persistent light wind data).

Although strong winds are seldom realized in the boundary layer, mean winds greater than 12.0 m/s do occur in the fall and winter with greater frequency than in other seasons. And, although winter has the greatest number of surface calms, each month during this season will average two or three days with gale force winds at places like Mould Bay. (Resolute Bay recorded combined low temperature and strong wind speeds that take the wind-chill factor off the chart.)

12.3.3 Summer Conditions

The most oustanding difference between this season and others is the lower frequencies of light mean mixed layer winds (Fig. 12.4 a). The highest frequency at this time occurs in the 4.0 to 8.0 m/s range (over 45% of the cases). At the same time, winds greater than 12.0 m/s occur least often.

In similar results compiled by Shaw et al (1972) it was found that persistent calm or light surface winds lasting 24 to 47 hours and greater than 48 hours occur least often in the summer. (The minimum frequency occurs in the Yukon and Northwest Territories). The average surface wind speed, however, is a minimum also. This means that in the summer the winds are light to moderate but relatively steady, while in the winter strong winds (normally associated with cold frontal passages) are interrupted by extended periods of light winds (Shaw et al, 1972).

The above observations are the result of weaker and less frequent synoptic systems in the summer compared to winter. Also, the mean north-westerly pressure gradient is weakest at this time. The quasistationary Arctic vortex fills as increasing sunlight and hemispheric warming erode the cold core. This process reaches a maximum in July, coincidental with the summer solstice.

The weak circulation accounts for the infrequent strong mean mixed layer winds. However, the greater frequency of mean winds between 4.0 and

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* NOTE: Cambridge Bay upper-air records were not available in this study - see Appendix D.

8.0 m/s is the result of, (1) less frequent surface-based inversions (except over ice and cold water surfaces), and (2) greater turbulent mixing layer heights. In addition, sea-breezes and valley winds assist the overall motion in the afternoon mixing layer.

12.3.4 Spring and Fall Conditions

There is considerable similarity in the mean mixed layer wind speed statistics between the spring and fall seasons. The calm to light mean wind speeds are more frequent than the other ranges. At the same time, mean winds greater than 12.0 m/s occur with the highest annual frequencies.

August, September, Feburary and March are generally stormy months across the High Arctic. Major changes in the airmass occur, as well as changes in the underlying surface. In addition, the intensity of local winds may be enhanced by local contrasts between relatively warmer open leads (in the fall) and cold snow or ice-packs. In these cases, the synoptic cyclonic circulation pattern will be superimposed by the vorticity generated from the underlying heat source.

12.4 VENTILATION COEFFICIENTS

Fig. 12.5 a indicates that over 80% of the annual cases are less than 3000 m^2/s. Only summer has a mean ventilation coefficient frequency less than 80% in this range. In winter, almost 100% of the cases fall in this high pollution potential category. In all seasons, the frequencies of conditions above 6000 m^2/s are less than 5% (Appendix B, Table 12.3). Maximum frequencies of the lowest conditions (i.e., less than 1000 m^2/s) occur over northeastern Ellesmere Island.

12.5 CONCLUSIONS

With the existence of the strong Arctic inversion in the winter and the generally light mean winds combined with comparatively low mixing heights in the summer, ventilation coefficients in the High Arctic are very low throughout the year. Only rarely are meteorological conditions favourable for high ventilation coefficients. These are most likely to occur in the summer, and least likely to occur in the fall and winter.

The Regional Summaries (Appendix C - Part 2, Tables 21 to 24) indicate that the High Arctic region ranks ahead of all other regions of Canada in having the highest frequencies of ventilation coefficients less than 6000 m^2/s in all seasons.

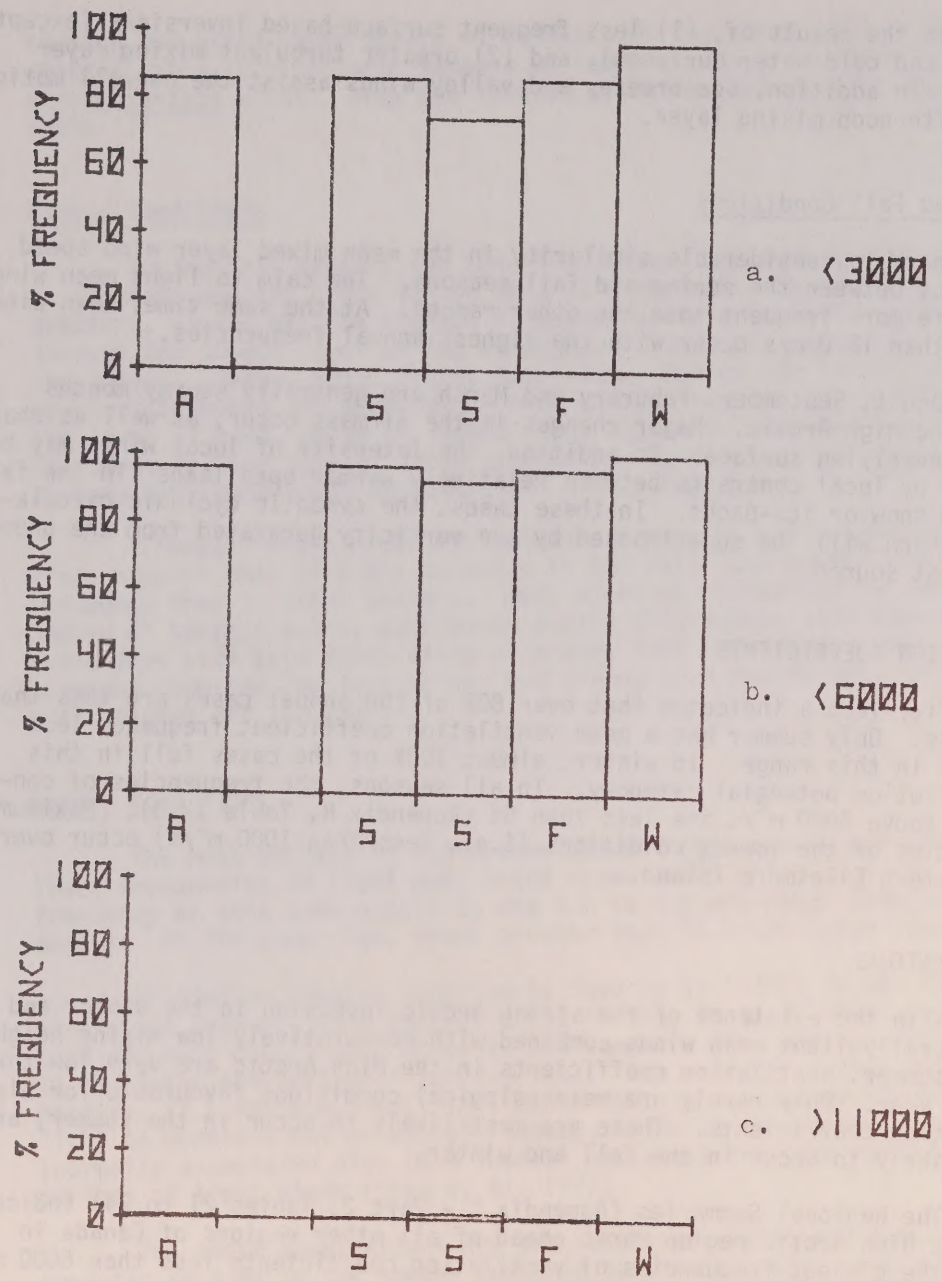

FIG. 12.5 Annual and Seasonal Frequencies of Occurrence of Afternoon Ventilation Coefficients (m^2/s) for the High Arctic Region

ACKNOWLEDGEMENT

I would like to extend thanks to R.V. Portelli, Head, Impact Assessment Section of the Air Quality and Inter-Environmental Research Branch, Atmospheric Environment Service, for his valuable guidance throughout this study. Thanks also go to J. Arnold for his helpful assistance in the preparation of the frequency distribution figures, and to C. Gauthier for her patient assistance in the preparation of the final manuscript.

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APPENDICES

LIST OF APPENDICES

APPENDIX A: Isopleth maps of seasonal and annual frequencies of occurrence of various ranges of the mixing depth parameters.

APPENDIX B: Frequency Distribution Tables - seasonal and annual percentage frequencies averaged over each of the twelve regions.

APPENDIX C: Part 1: Regional Summaries - seasonal and annual frequencies are summarized for significant levels.
Part 2: Regional Comparisons - regions are ranked in order of decreasing frequencies.

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APPENDIX E: Special Cases (C-, U- and M - type).

APPENDIX F: Atmospheric Areas of the U.S.

APPENDIX A

APPENDIX A

Percentage Frequency Charts

Seasonal and Annual Percentage Frequency of:

A.I Maximum (Afternoon) Mixing Heights:
Analysed every 200 m from 0.0 to 199 m
to 2000 m + .

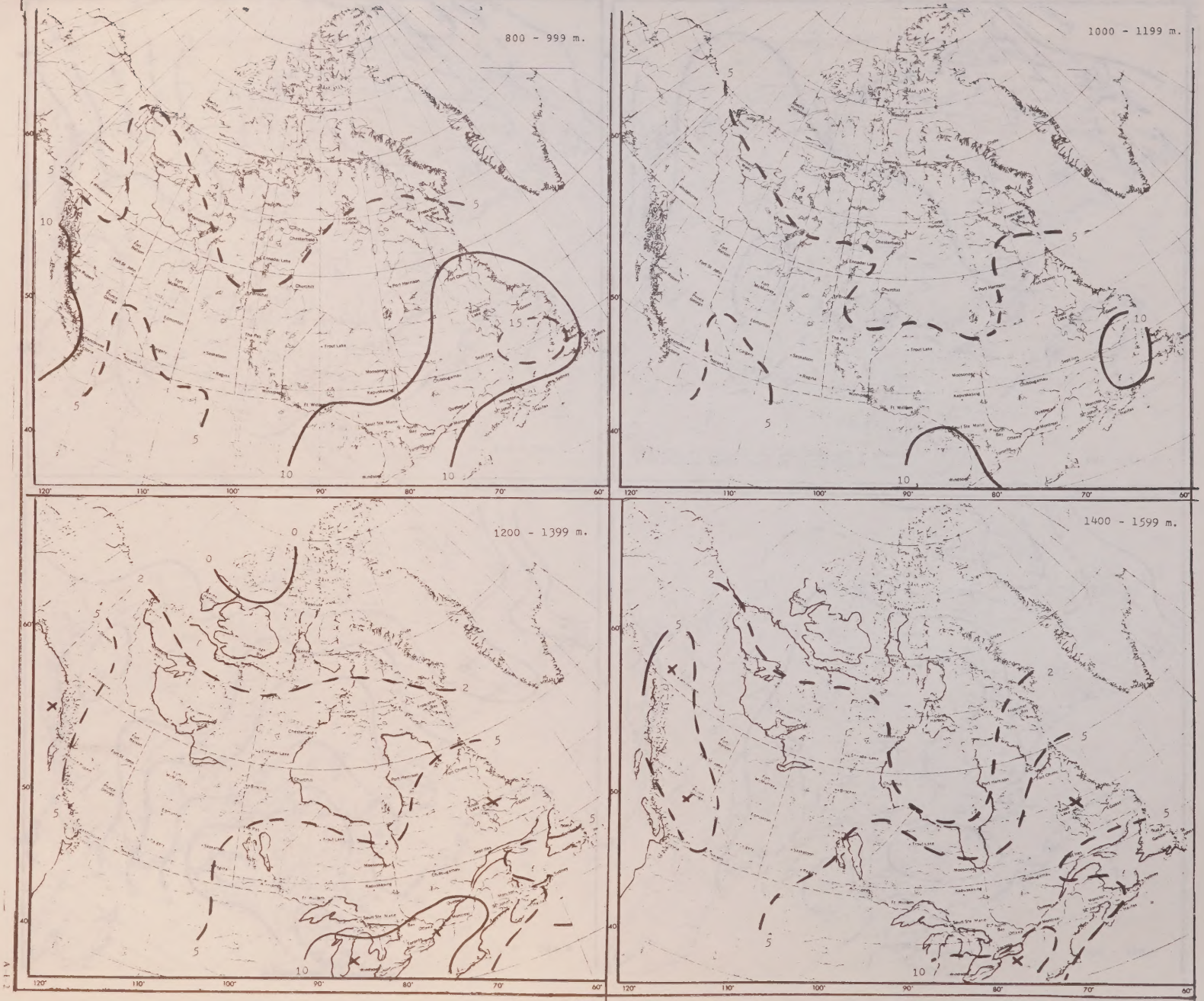
A.II Mean Transport Wind Speed Through the Mixed Layer:
Analysed every 4.0 m/s from 0.0 to 4.0 m/s
to 20.0 m/s +.

A.III Ventilation Coefficient:
Analysed every 1000 m^2/s from 0.0 to 1000 m^2/s
to 11000 m^2/s +.

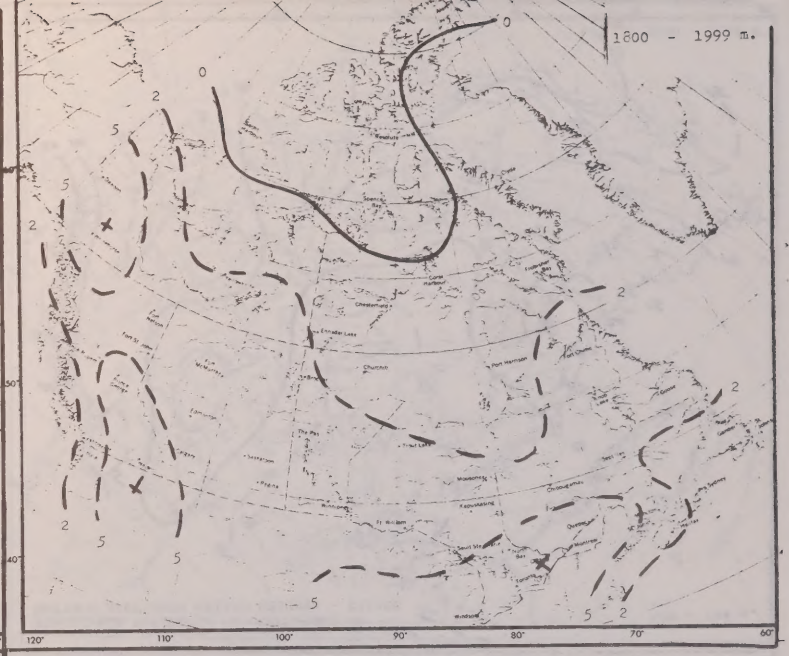
APPENDIX A.I

MAXIMUM AFTERNOON
MIXING HEIGHTS

0.0 - 199 m
200 - 399 m
400 - 599 m
600 - 799 m
PERCENTAGE FREQUENCY OF OCCURRENCE OF
MAXIMUM AFTERNOON MIXING HEIGHTS - ANNUAL

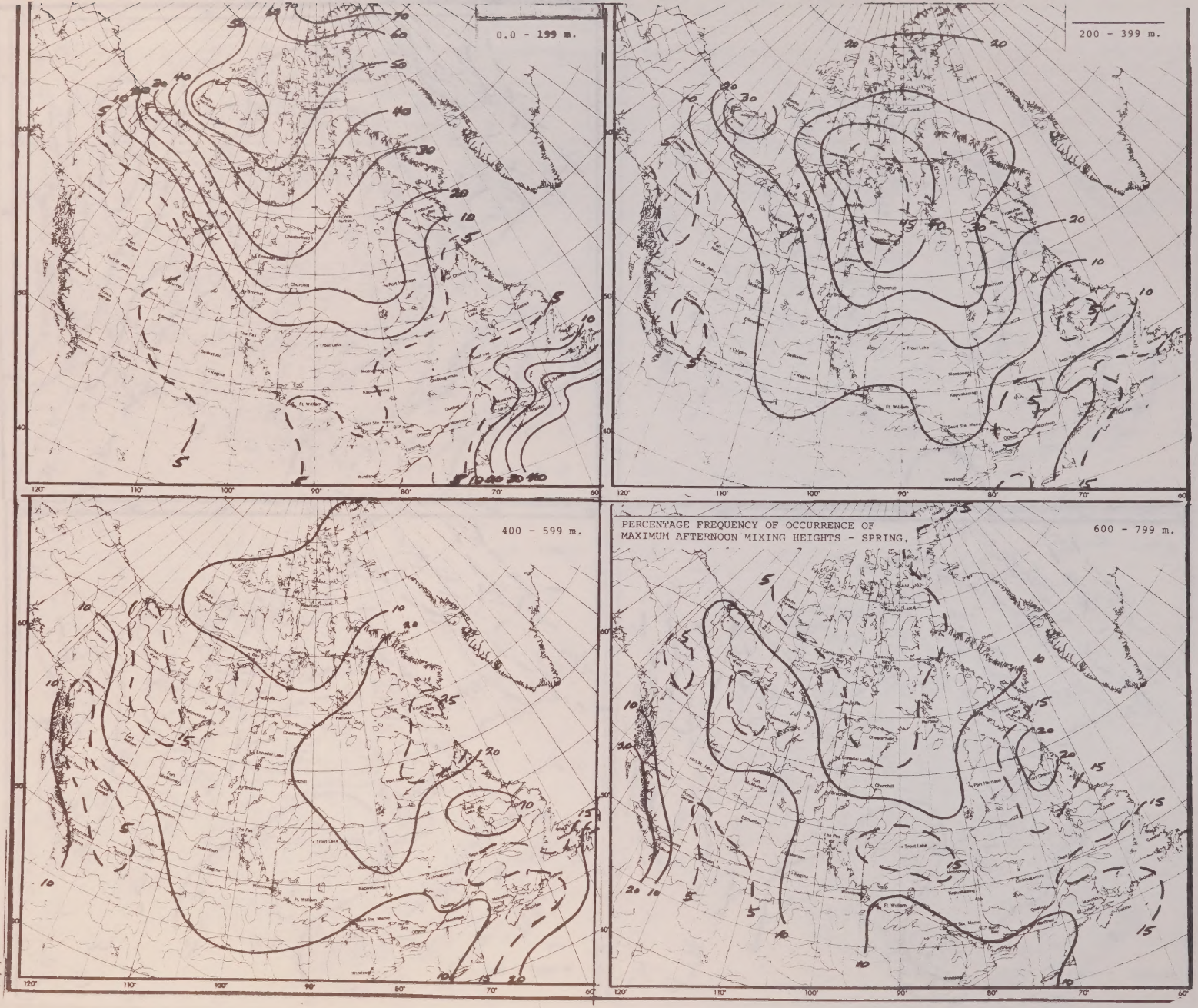

800 - 999 m.
1000 - 1199 m.
1200 - 1399 m.
1400 - 1599 m.

1600 - 1799 m.
0
2
5
120°
110°
100°
90°
80°
70°
60°
50°
40°


1800 - 1999 m.
0
2
5
120°
110°
100°
90°
80°
70°
60°
50°
40°

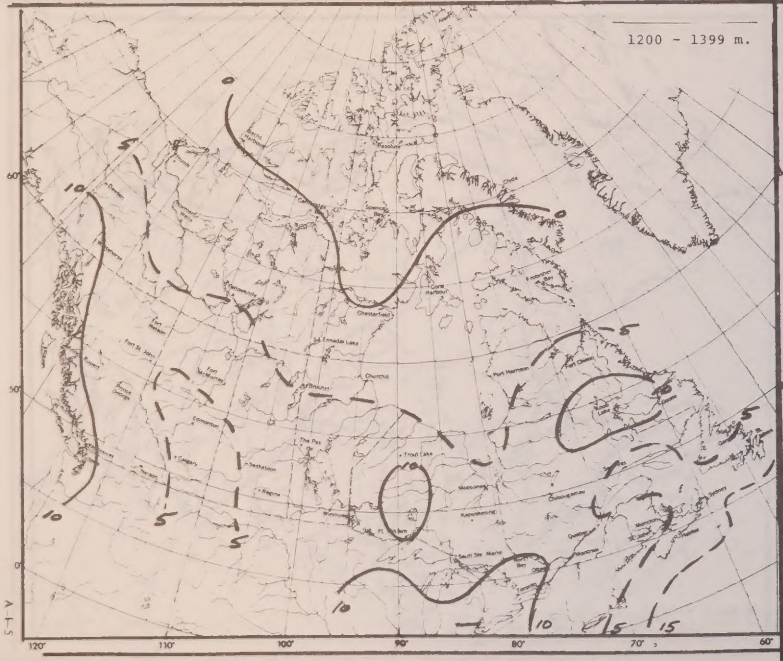
2000 m.
5
10
20
30
15
120°
110°
100°
90°
60°
50°
40°

A-1-3


0.0 - 199 m.
200 - 399 m.
400 - 599 m.
600 - 799 m.
PERCENTAGE FREQUENCY OF OCCURRENCE OF
MAXIMUM AFTERNOON MIXING HEIGHTS - SPRING.

800 - 999 m.

1000 - 1199 m.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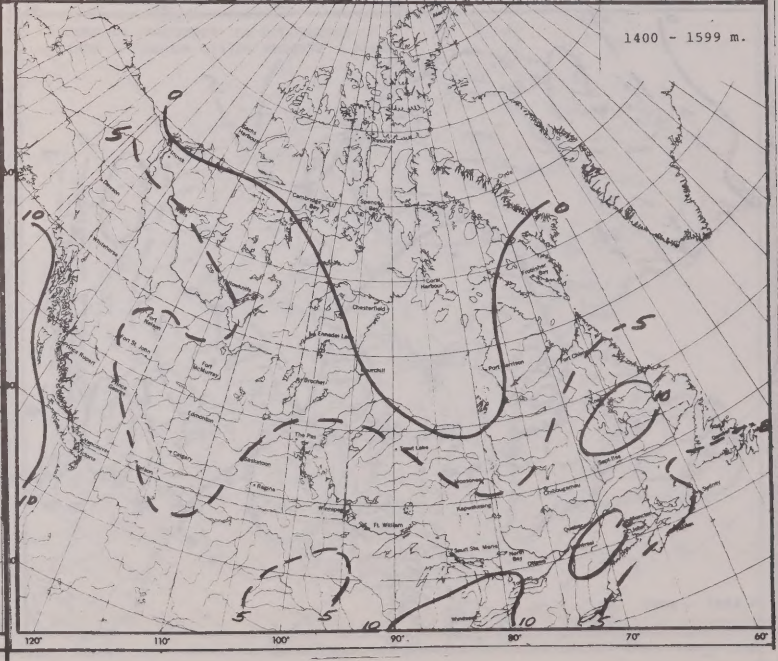
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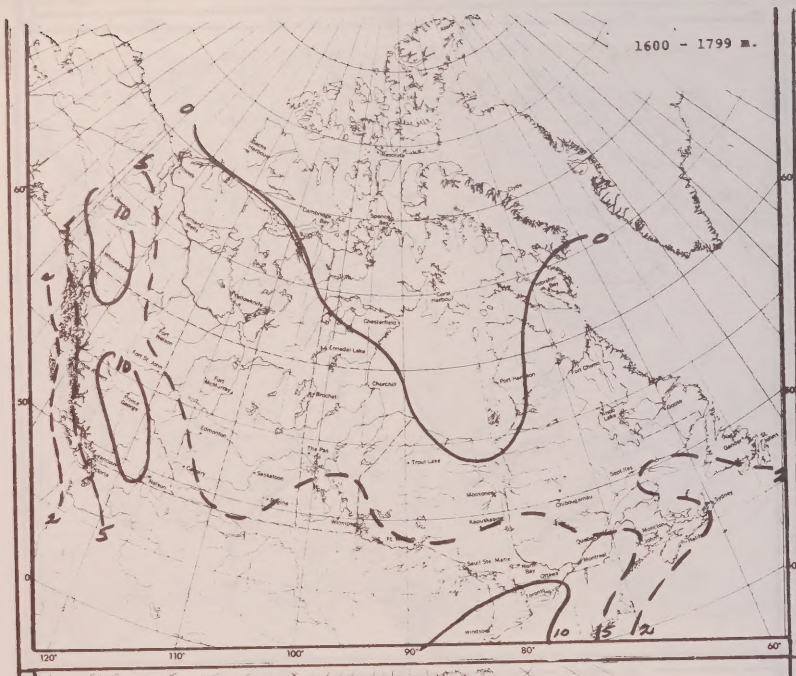
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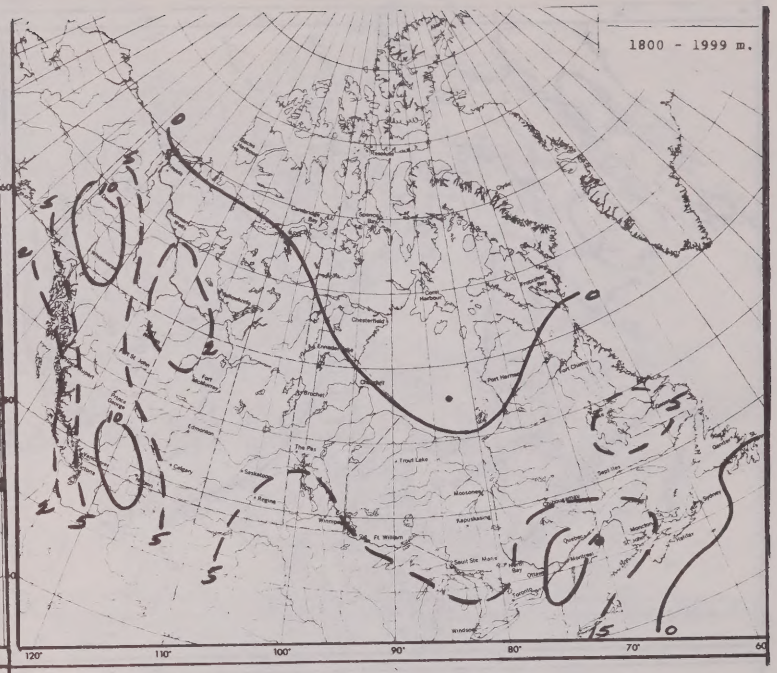
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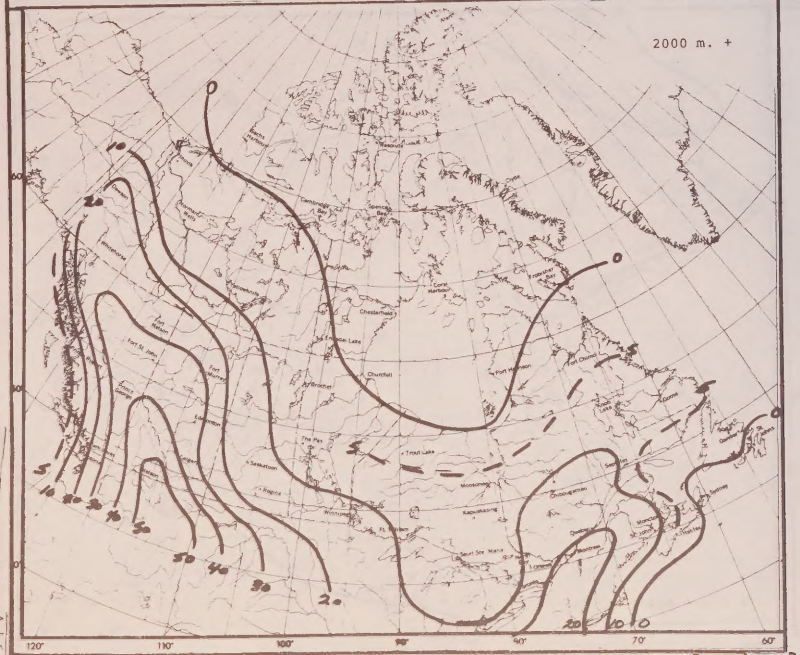
2000 m. +

0.0 - 199 m.
200 - 399 m.
400 - 599 m.
600 - 799 m.
PERCENTAGE FREQUENCY OF OCCURRENCE OF
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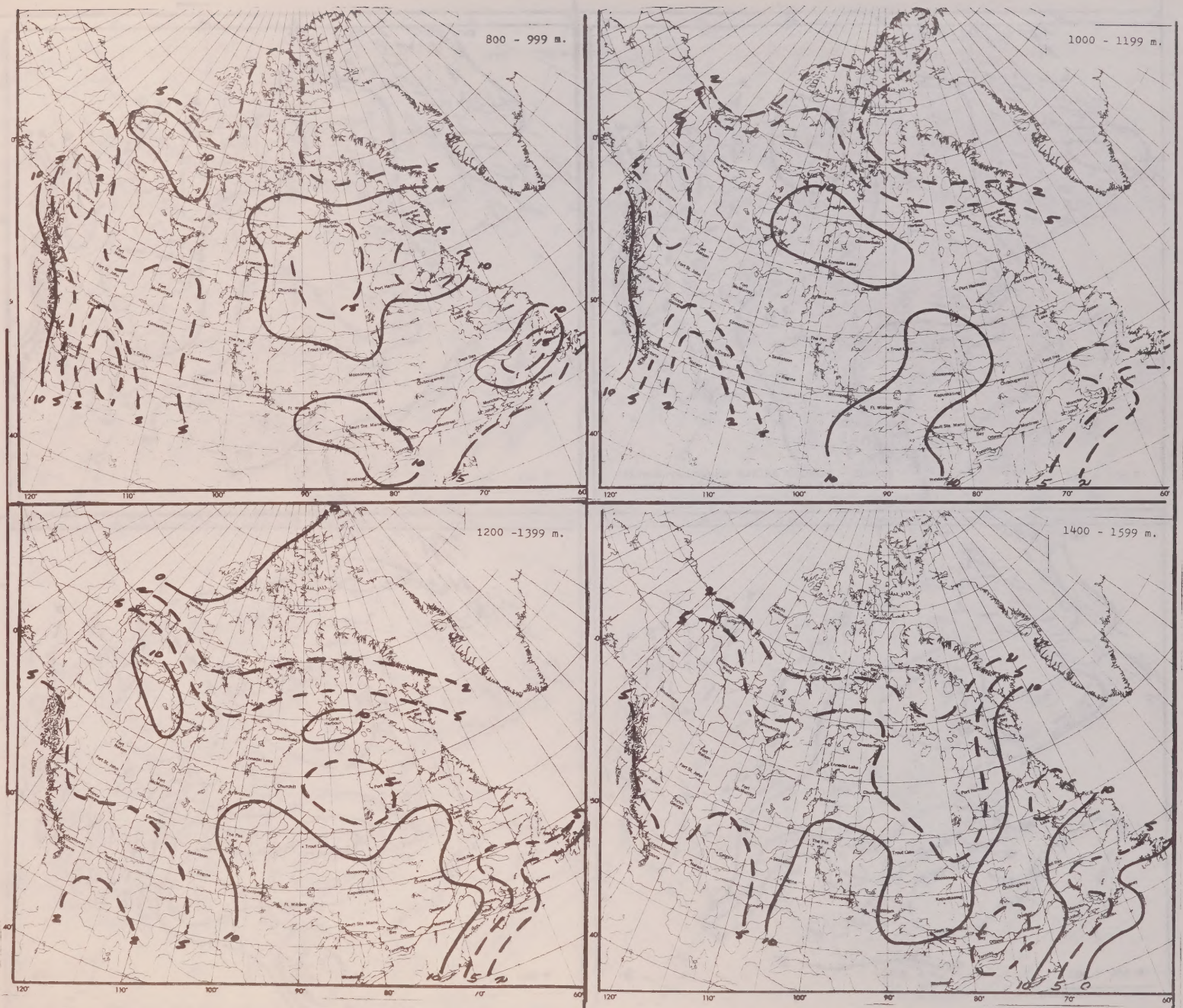
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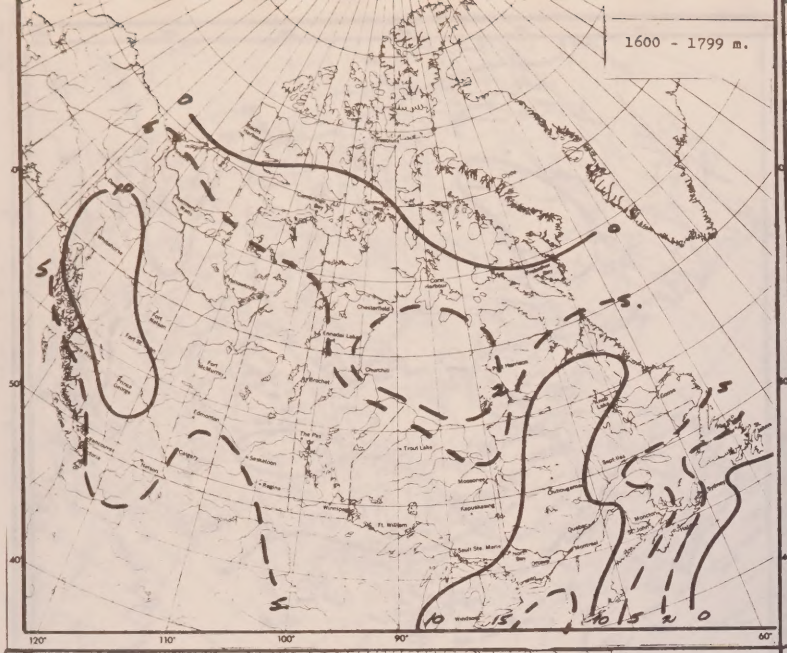
1000 - 1199 m.
1200 -1399 m.
1400 - 1599 m.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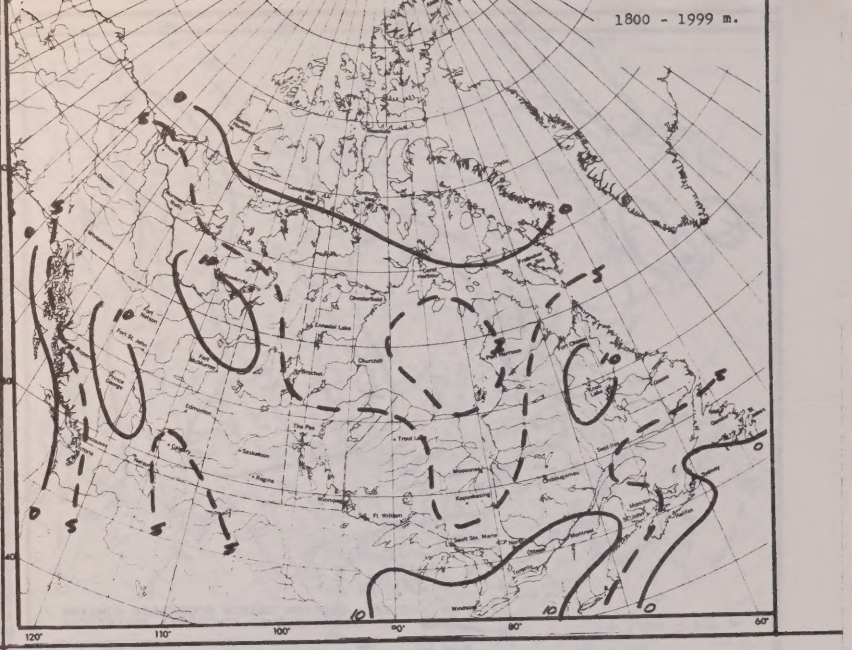
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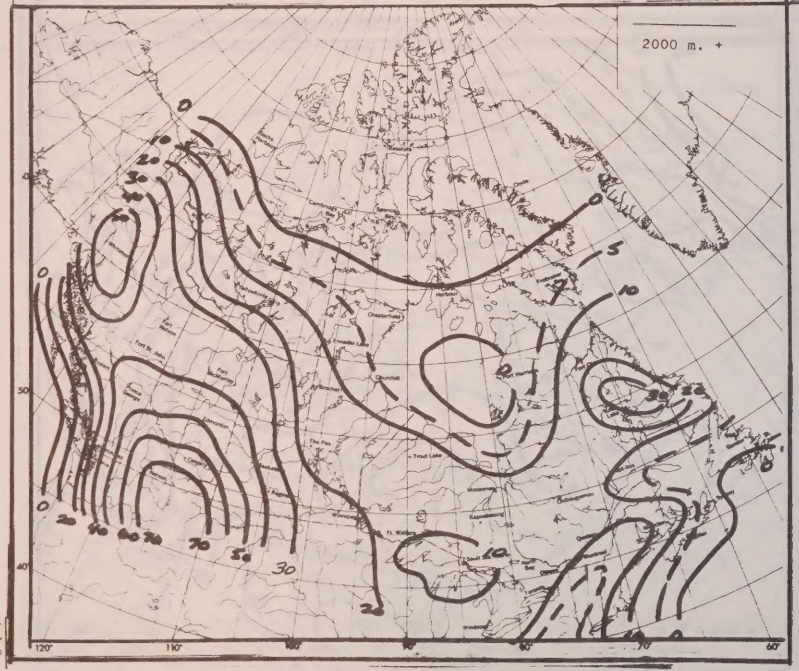
2000 m. +

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200 - 399 m.
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600 - 799 m.
PERCENTAGE FREQUENCY OF OCCURRENCE OF
MAXIMUM AFTERNOON MIXING HEIGHTS - FALL.

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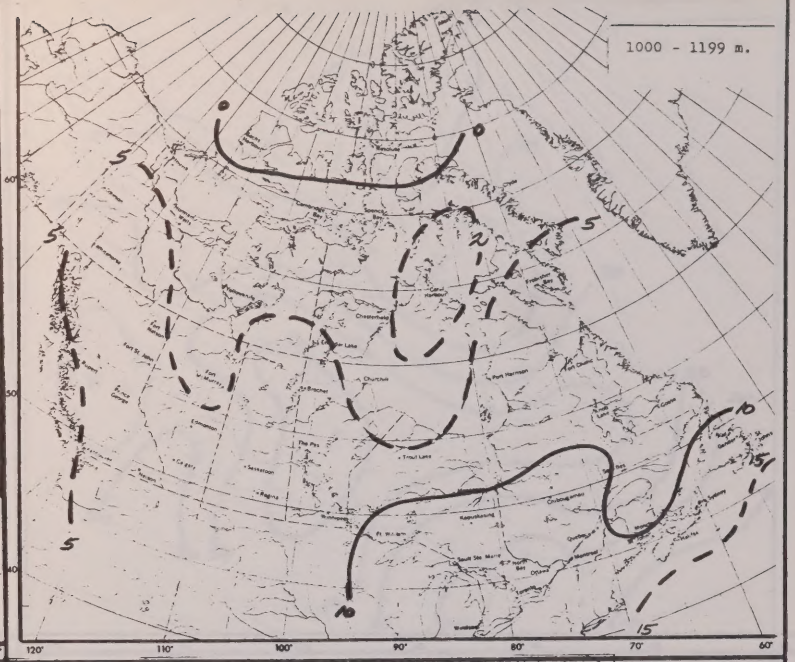
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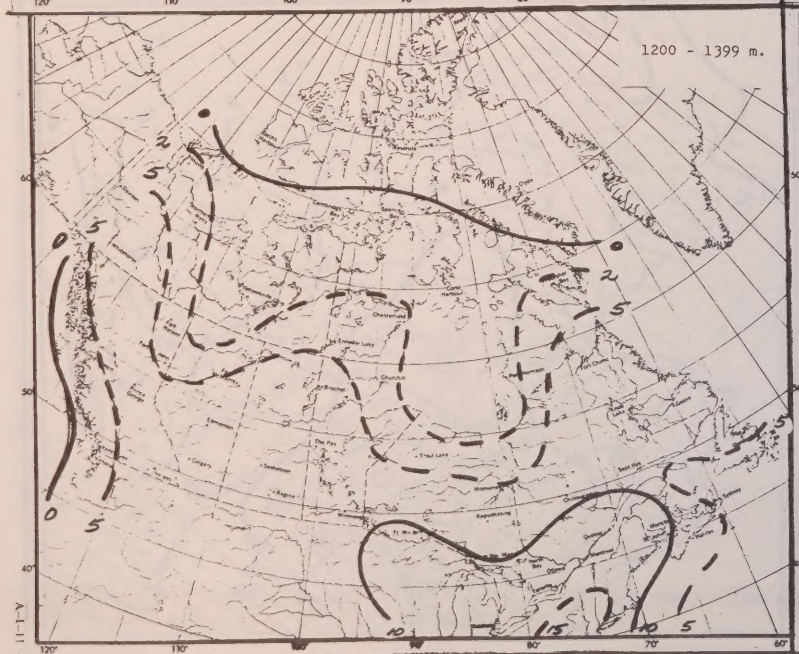
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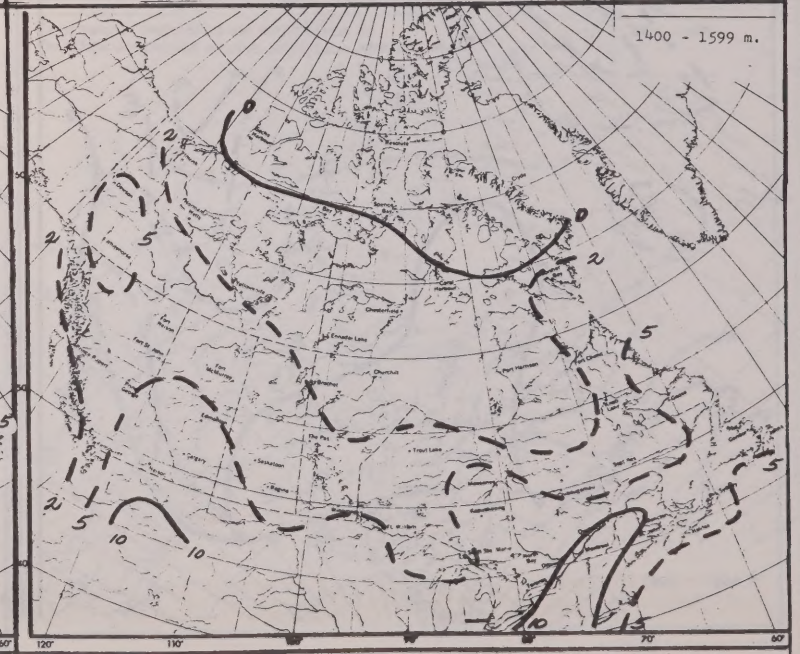
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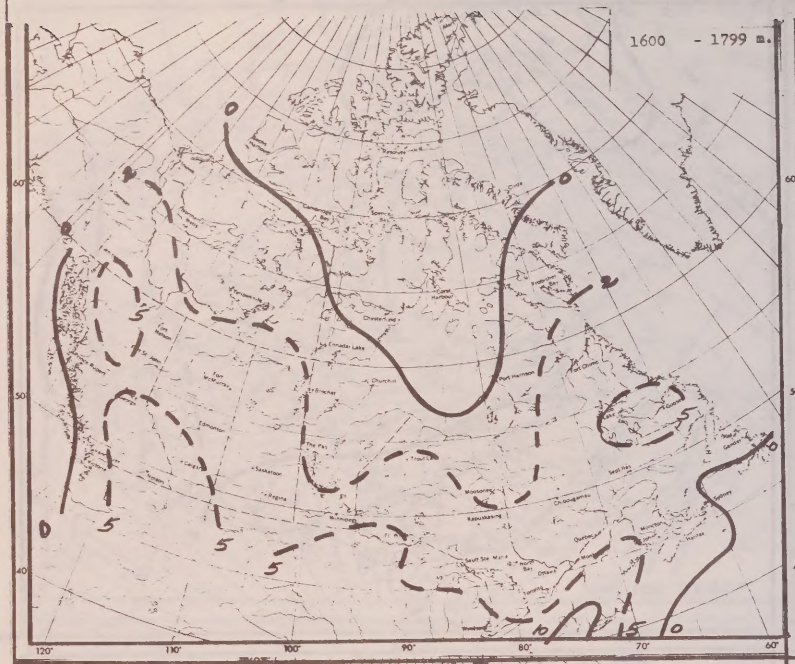
1600 - 1799 m.
120°
110°
100°
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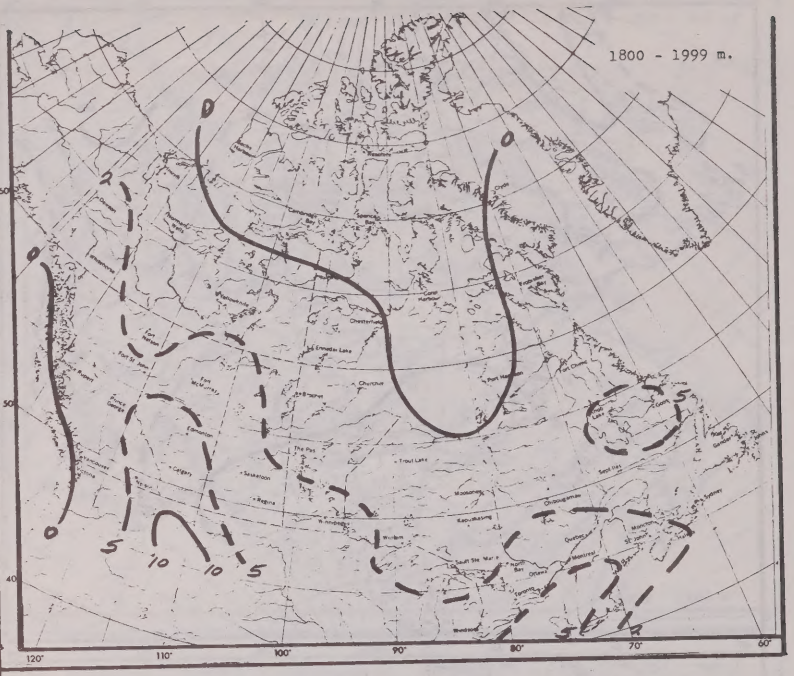
80°
70°
60°
60°
50°
40°


1800 - 1999 m.
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100°
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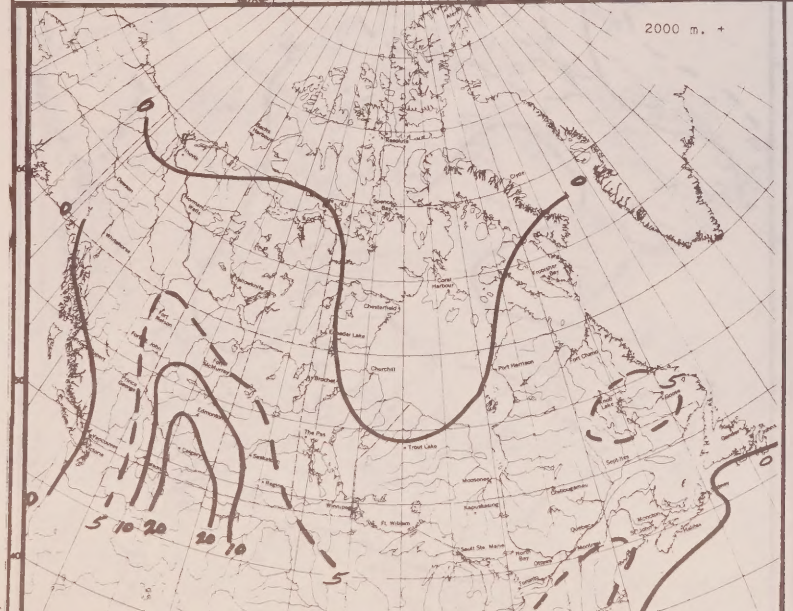
70°
60°
60°
50°
40°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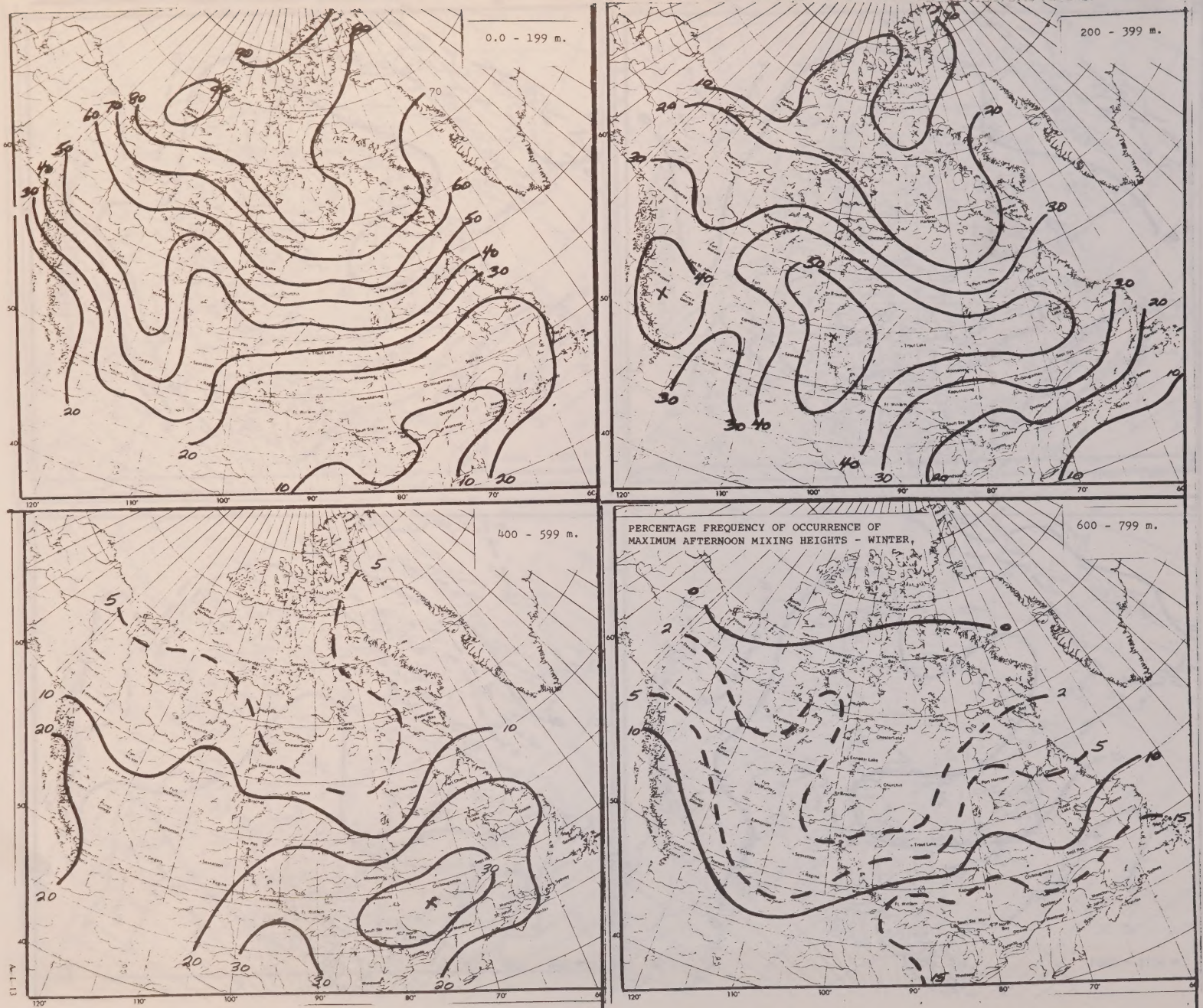
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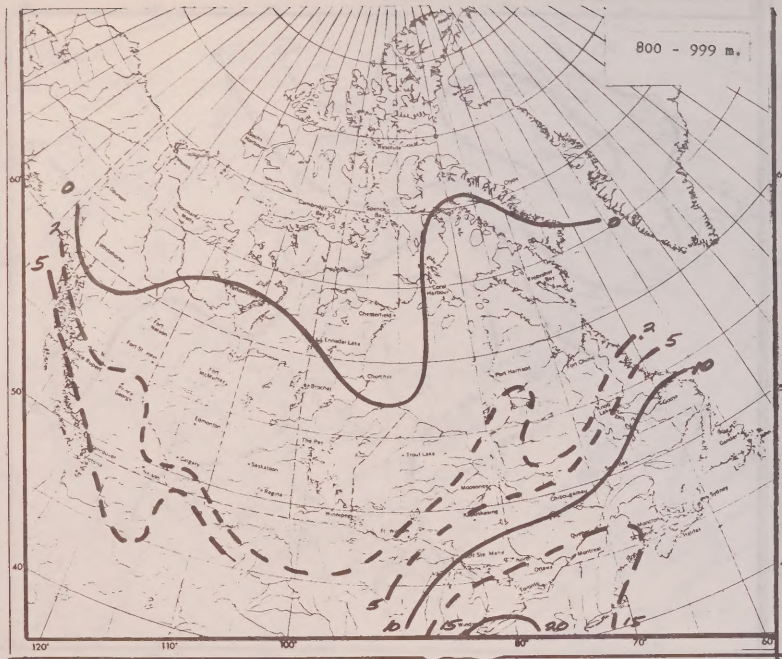
400 - 599 m.
600 - 799 m.
PERCENTAGE FREQUENCY OF OCCURRENCE OF
MAXIMUM AFTERNOON MIXING HEIGHTS - WINTER,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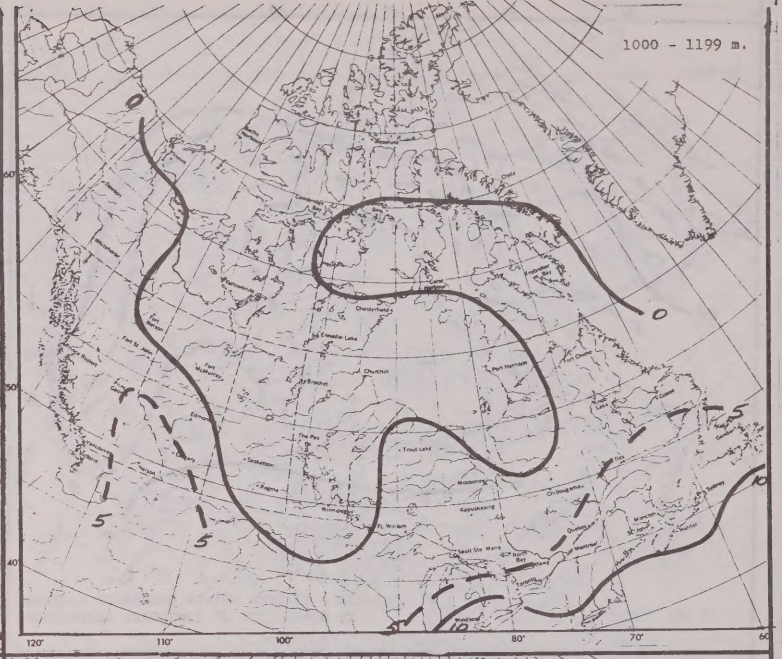
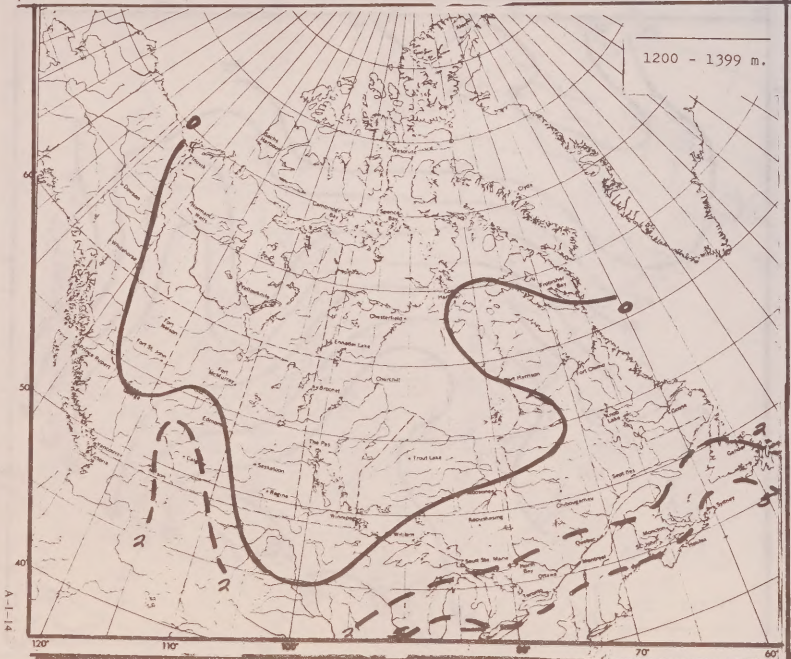

1000 - 1199 m.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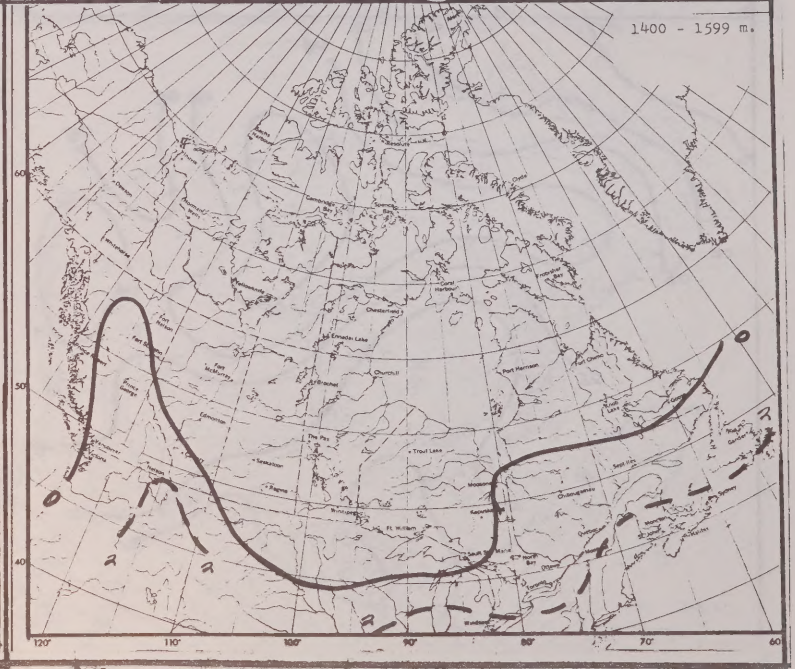
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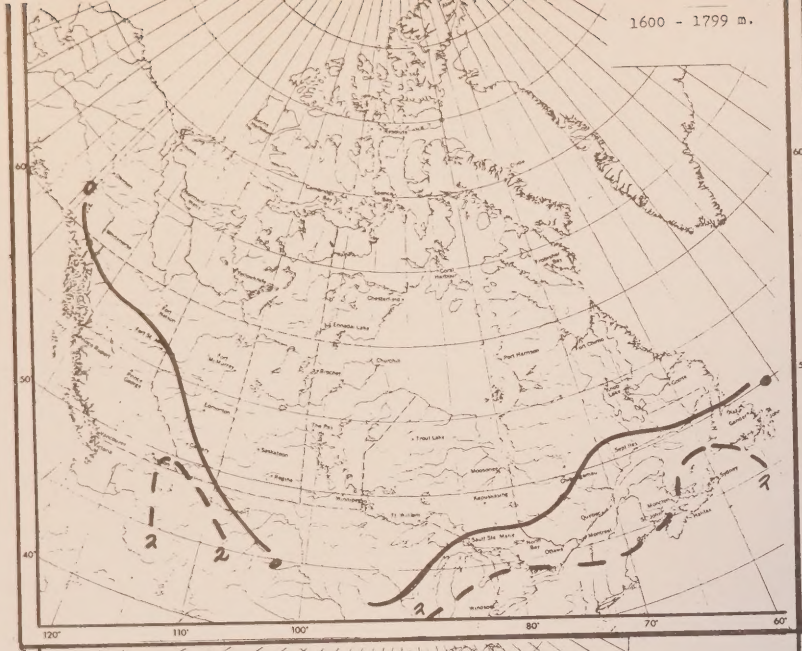
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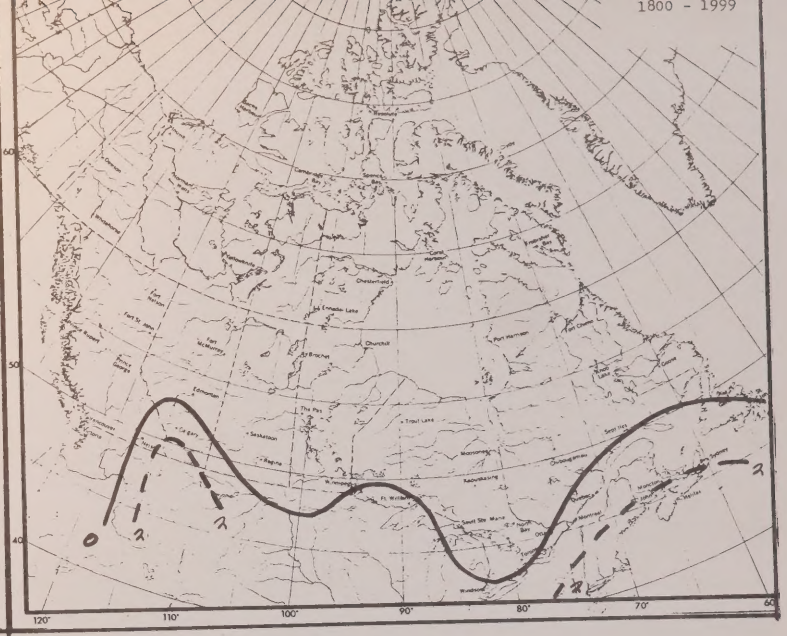
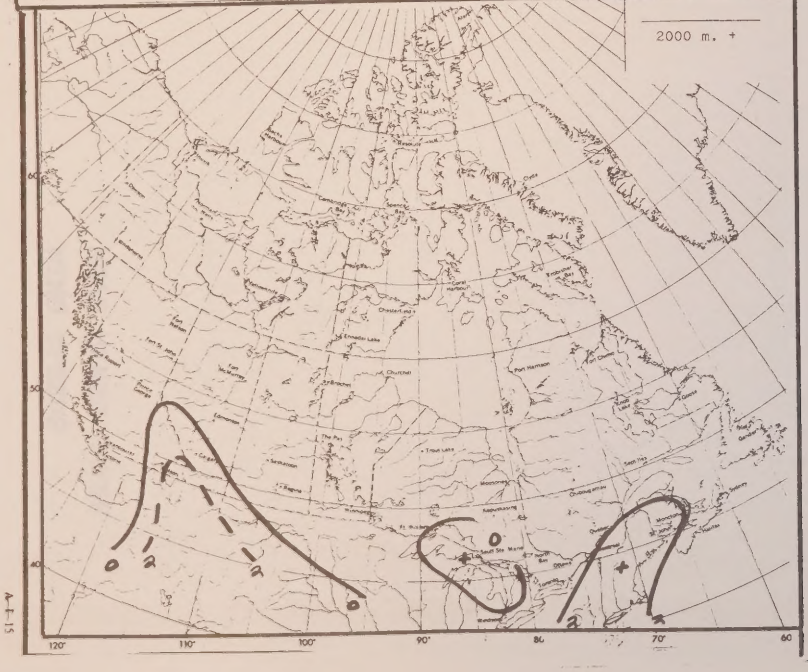

1800 - 1999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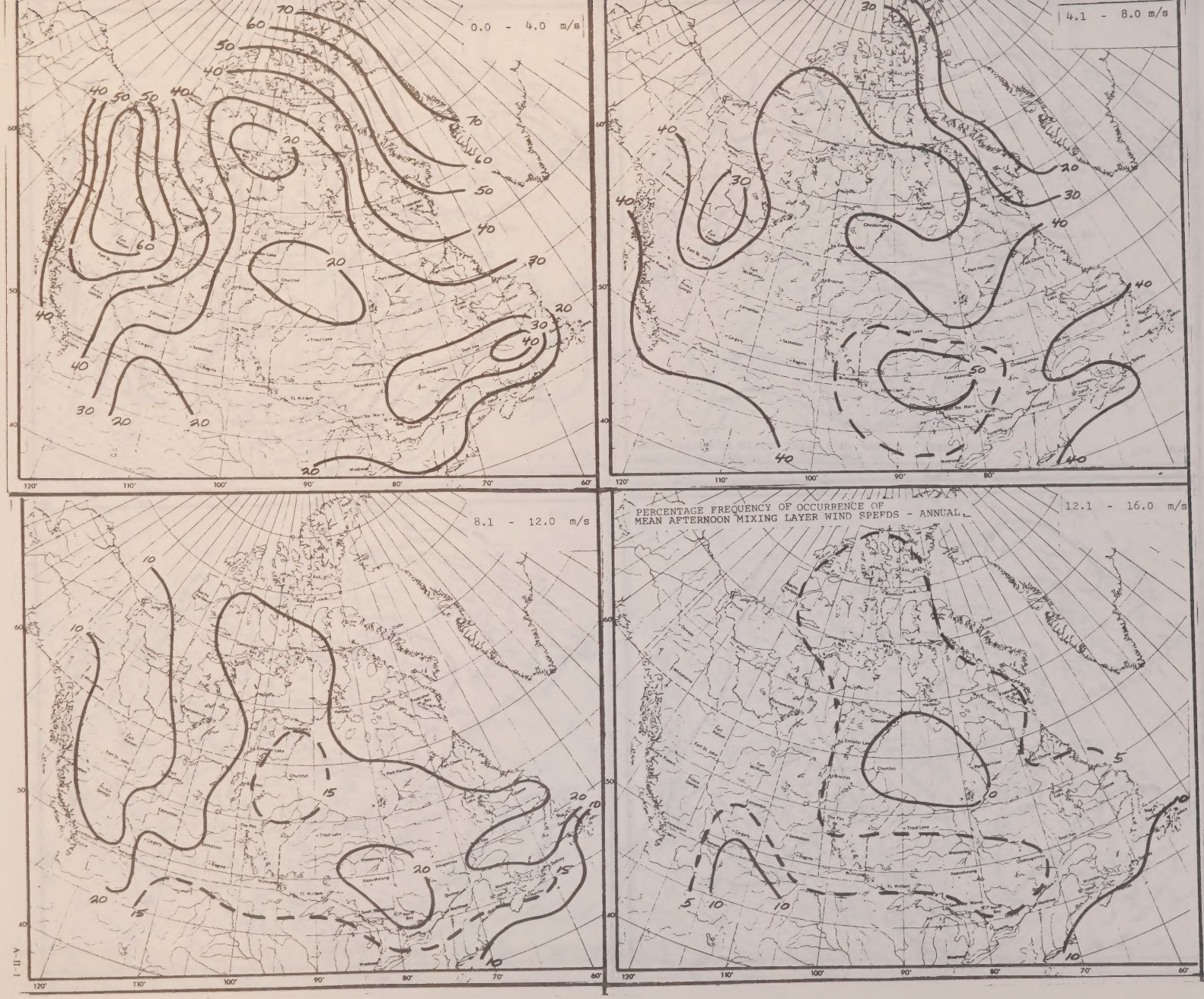
APPENDIX A.II

MEAN MIXED LAYER
WIND SPEEDS


PERCENTAGE FREQUENCY OF OCCURRENCE OF
MEAN AFTERNOON MIXING LAYER WIND SPEEDS - ANNUAL
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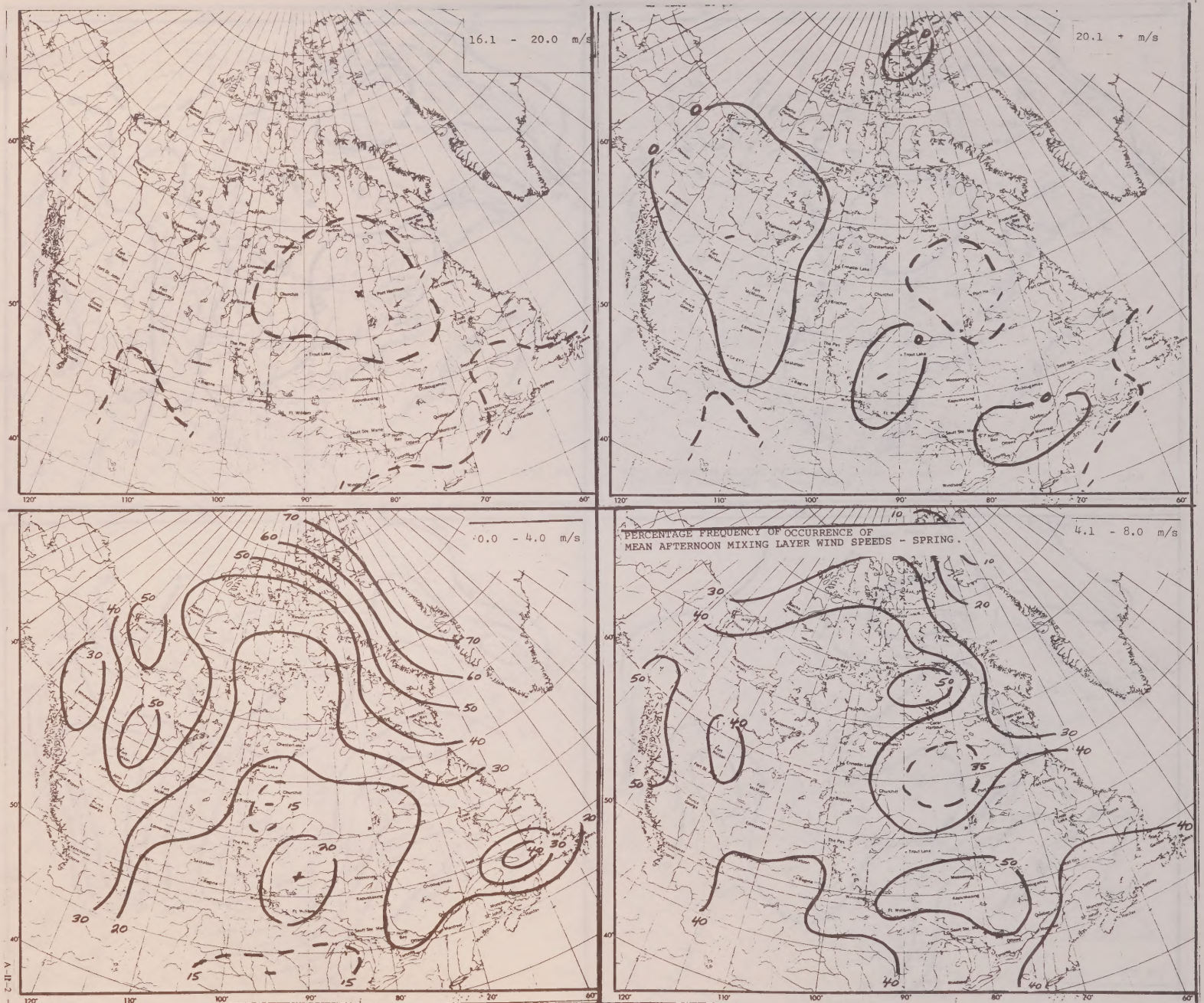
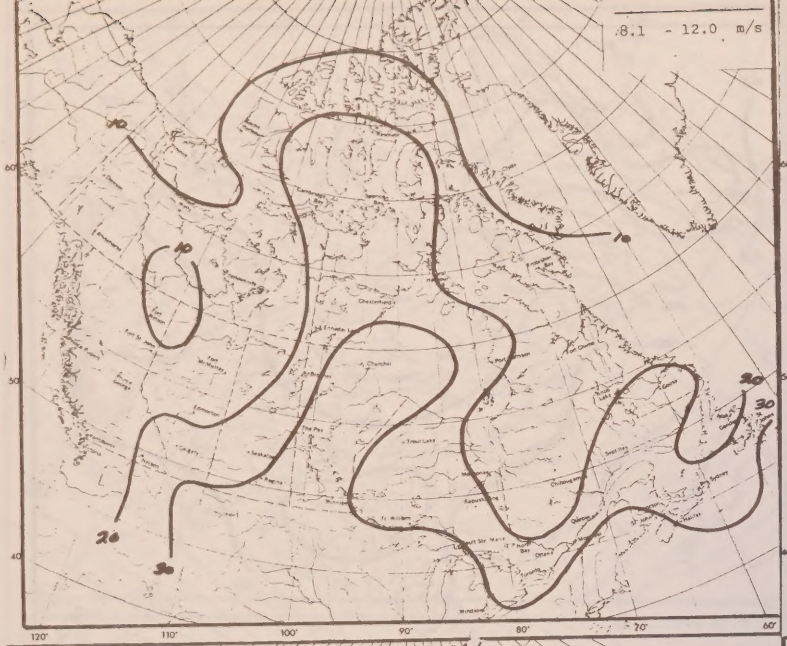
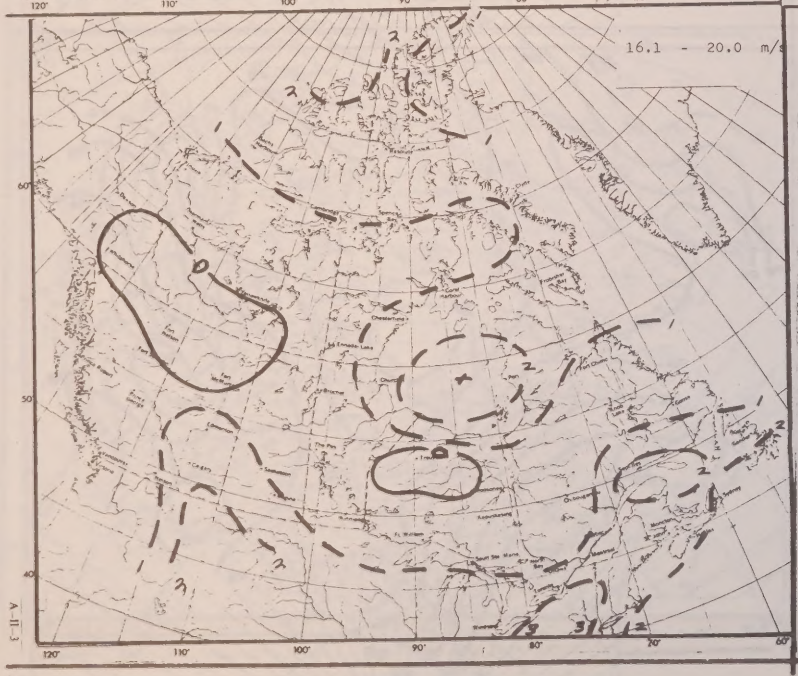
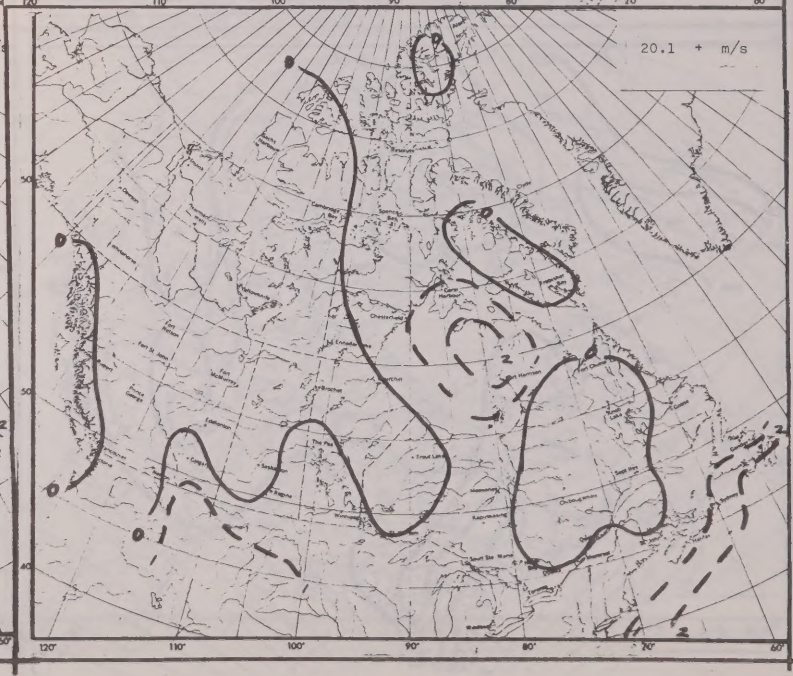
4.1 - 8.0 m/s
8.1 - 12.0 m/s
12.1 - 16.0 m/s


16.1 - 20.0 m/s
20.1 + m/s
0.0 - 4.0 m/s
4.1 - 8.0 m/s
PERCENTAGE FREQUENCY OF OCCURRENCE OF
MEAN AFTERNOON MIXING LAYER WIND SPEEDS - SPRING.


8.1 - 12.0 m/s
10
10
20
30
20
30
120°
110°
100°
90°
80°
70°
60°
50°
40°

12.1 - 16.0 m/s
5
2
10
5
10
120°
110°
100°
90°
80°
70°
60°
50°
40°


16.1 - 20.0 m/s
2
0
2
2
2
120°
110°
100°
90°
80°
70°
60°
50°
40°


20.1 + m/s
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0
0
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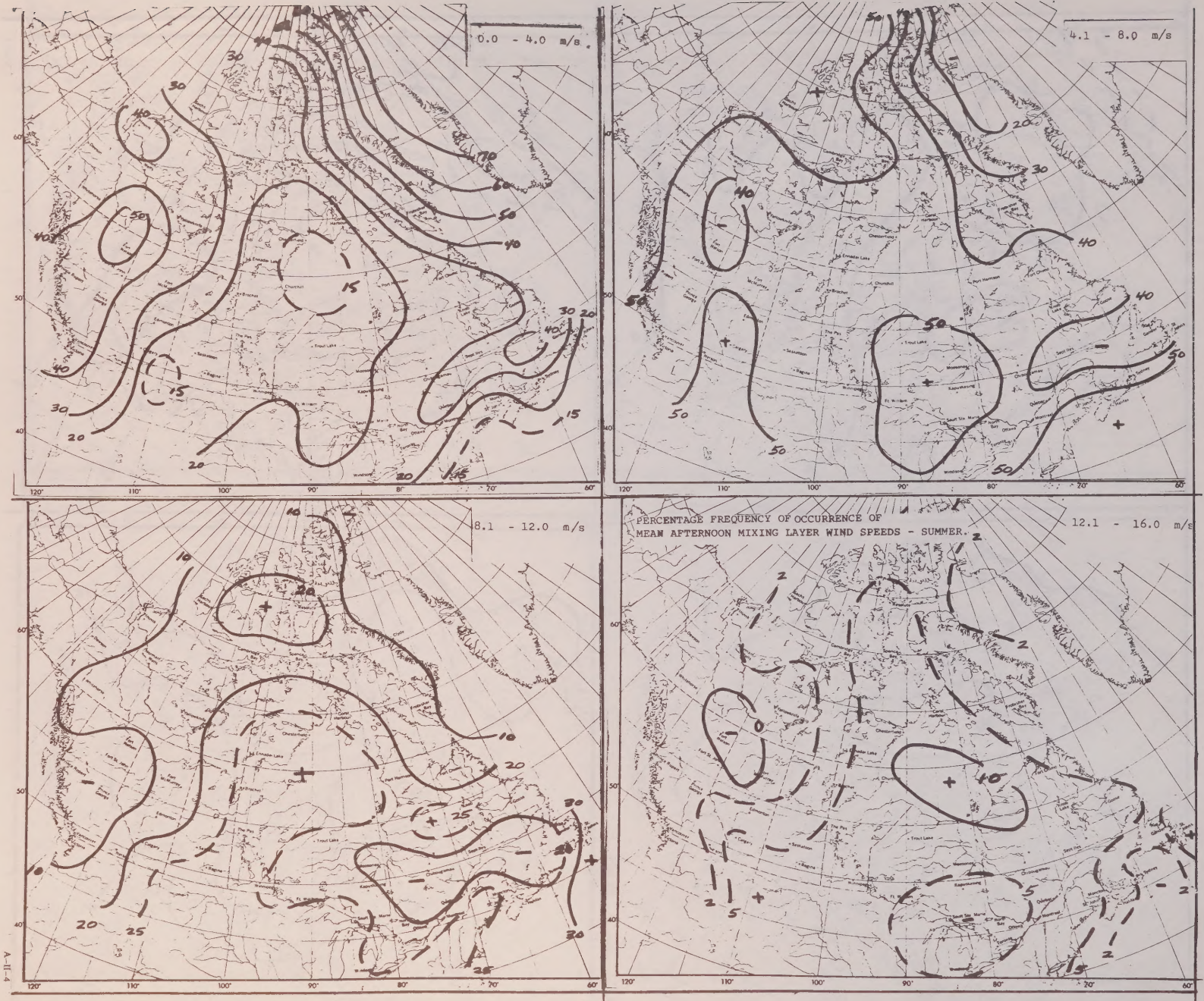
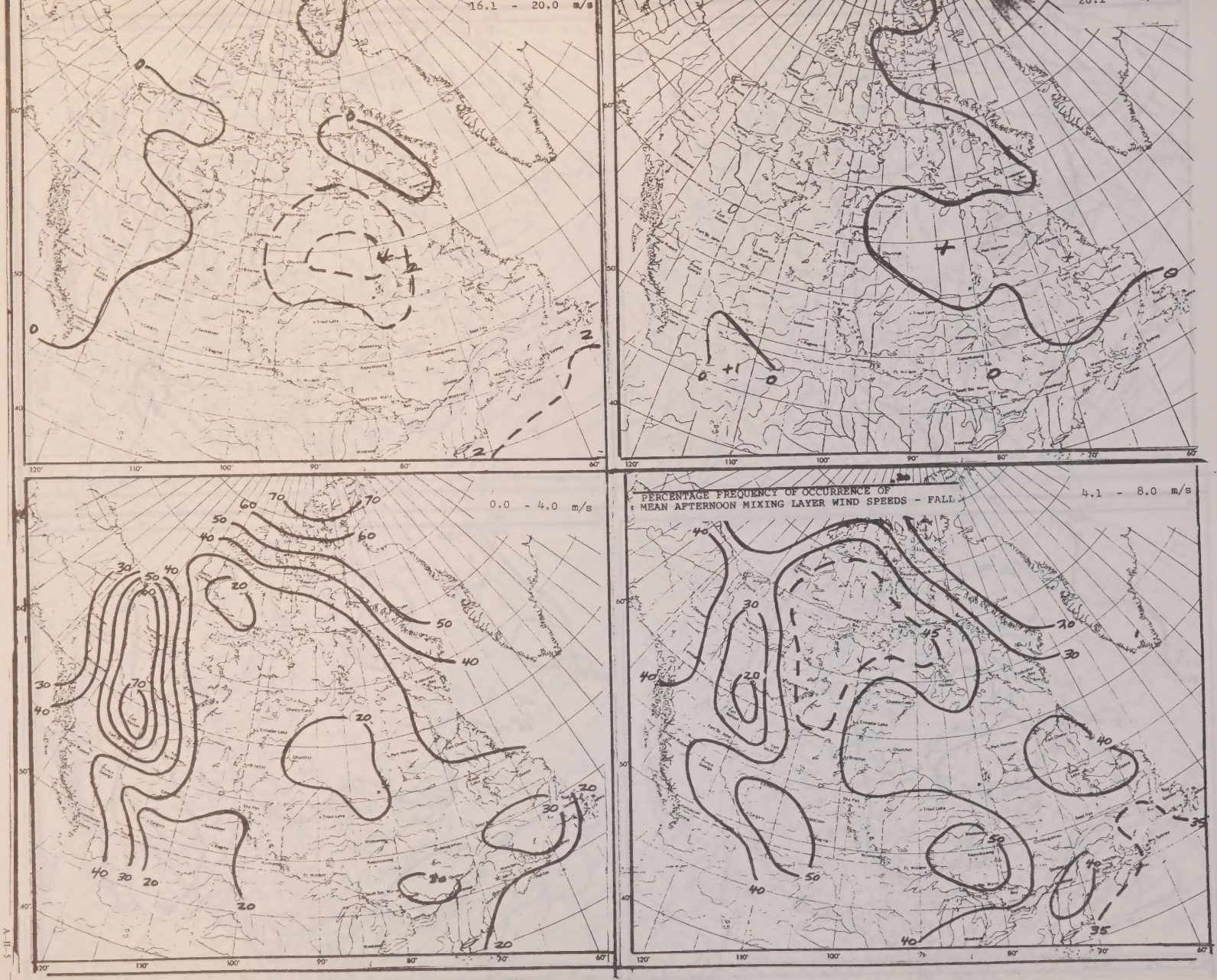
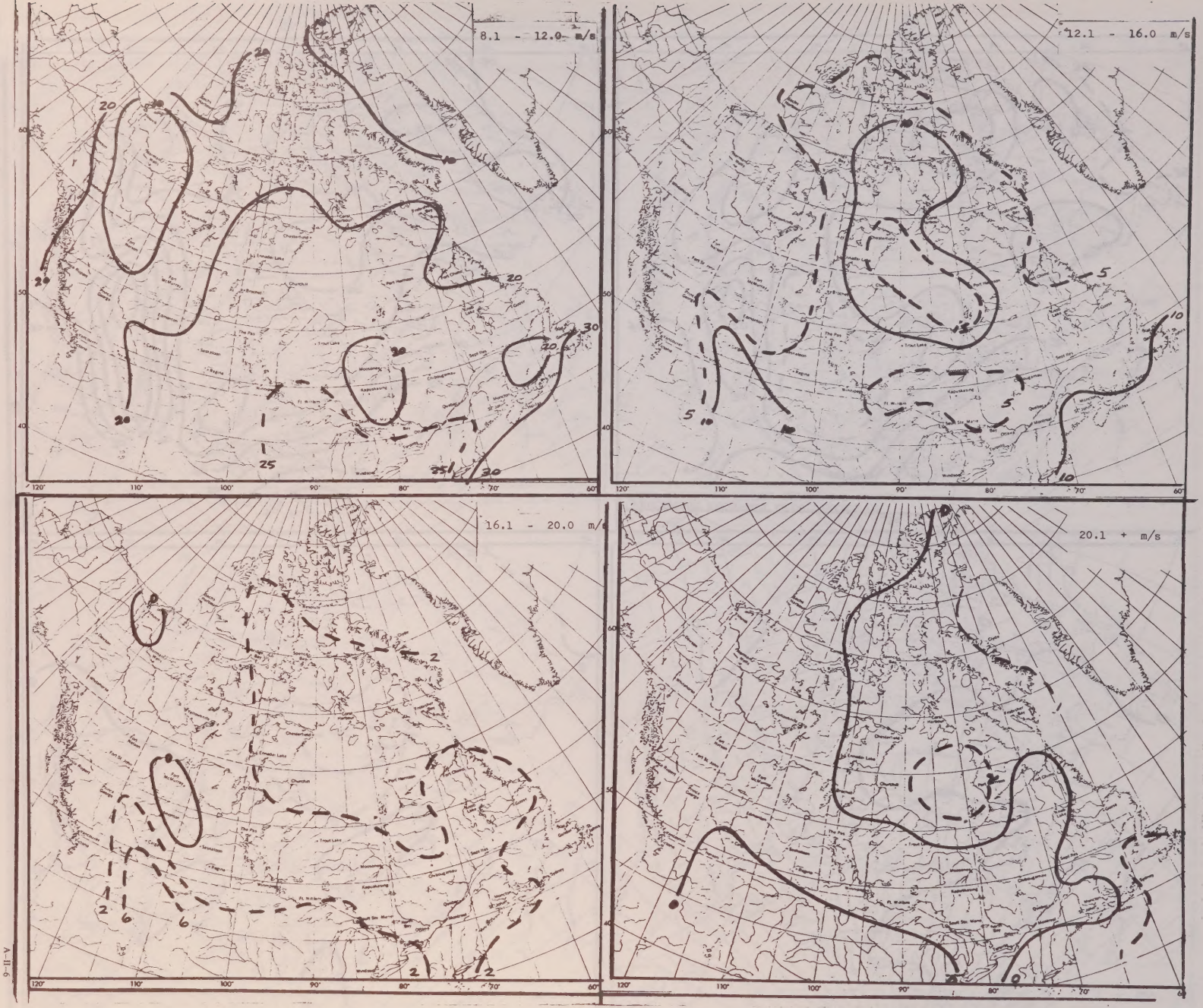
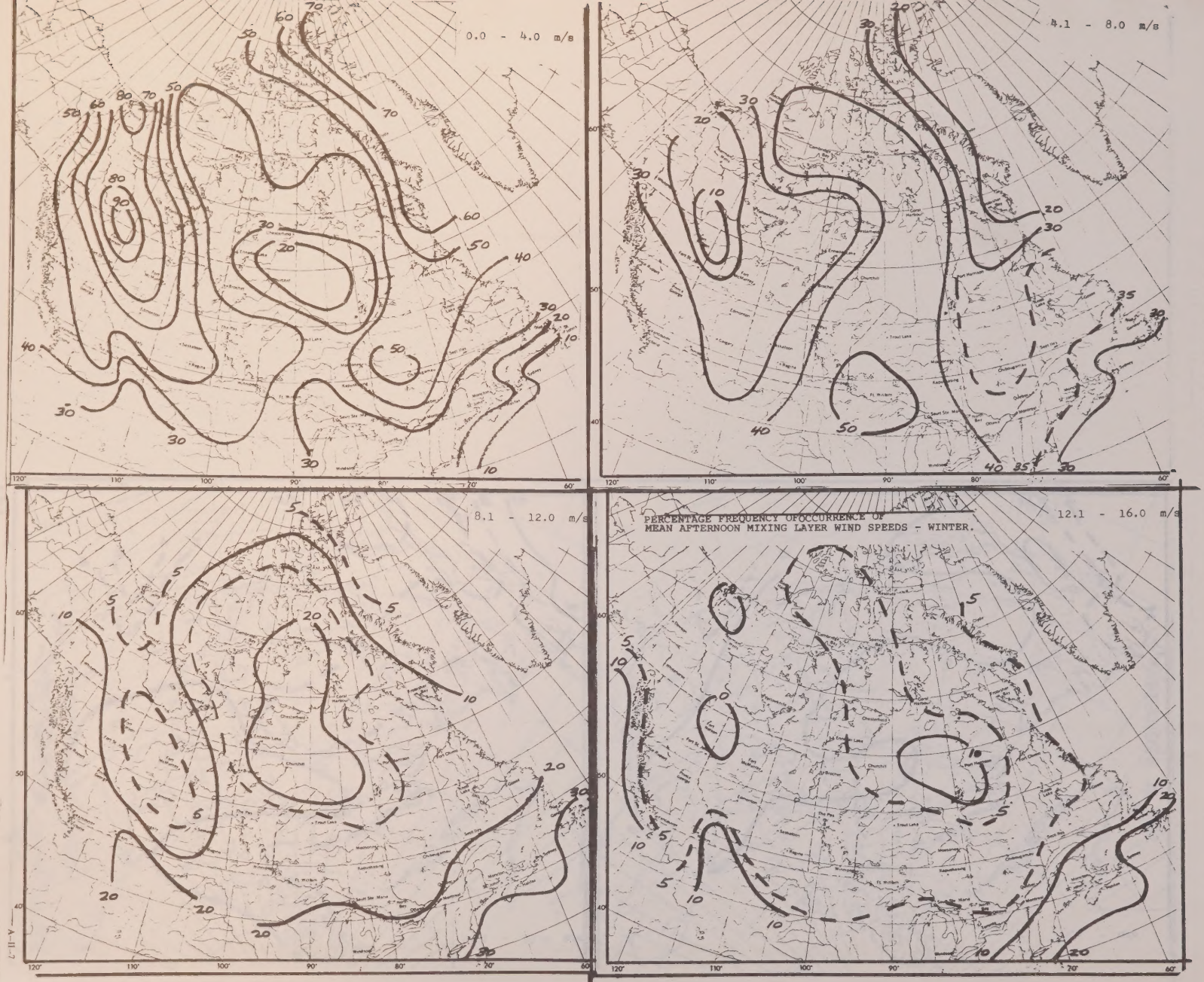
110°
100°
90°
80°
70°
60°
50°
40°

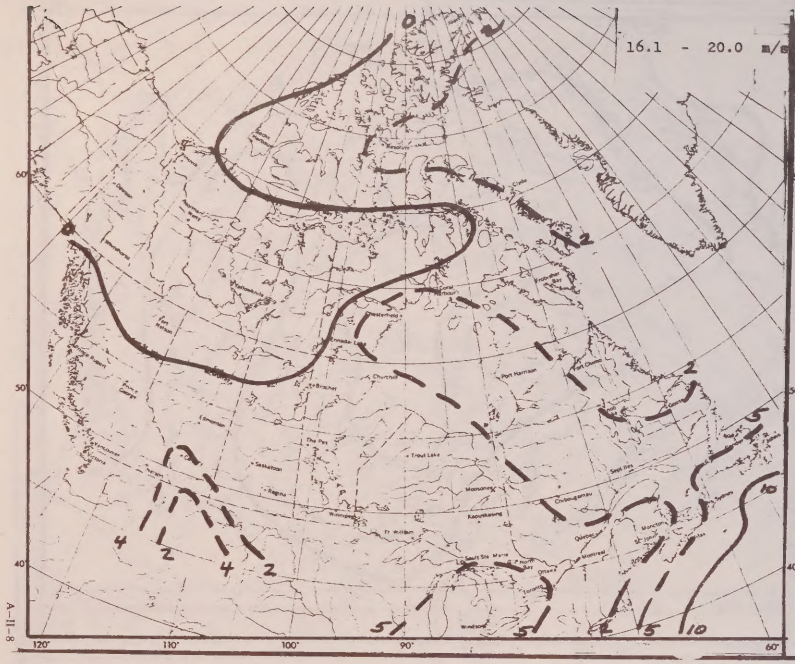

0.0 - 4.0 m/s
4.1 - 8.0 m/s
8.1 - 12.0 m/s
12.1 - 16.0 m/s
PERCENTAGE FREQUENCY OF OCCURRENCE OF
MEAN AFTERNOON MIXING LAYER WIND SPEEDS - SUMMER.

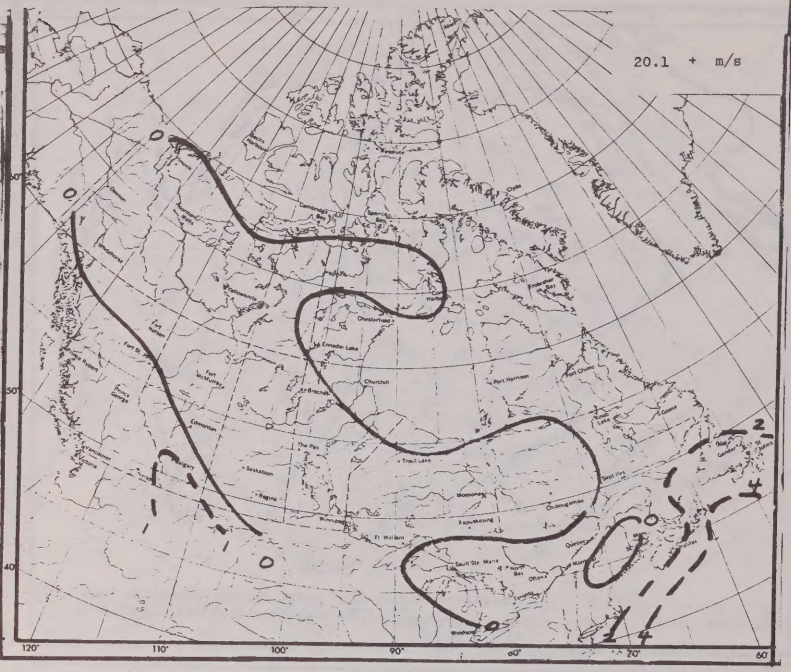

16.1 - 20.0 m/s
0.0 - 4.0 m/s
4.1 - 8.0 m/s
PERCENTAGE FREQUENCY OF OCCURRENCE OF
MEAN AFTERNOON MIXING LAYER WIND SPEEDS - FALL


8.1 - 12.0 m/s
12.1 - 16.0 m/s
16.1 - 20.0 m/s
20.1 + m/s



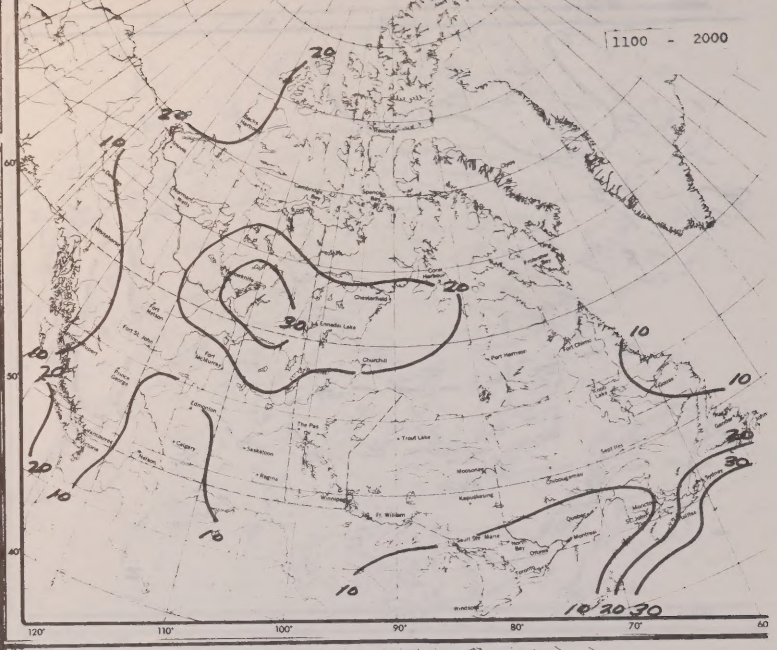
PERCENTAGE FREQUENCY OFOCCURRENCE OF MEAN AFTERNOON MIXING LAYER WIND SPEEDS - WINTER.

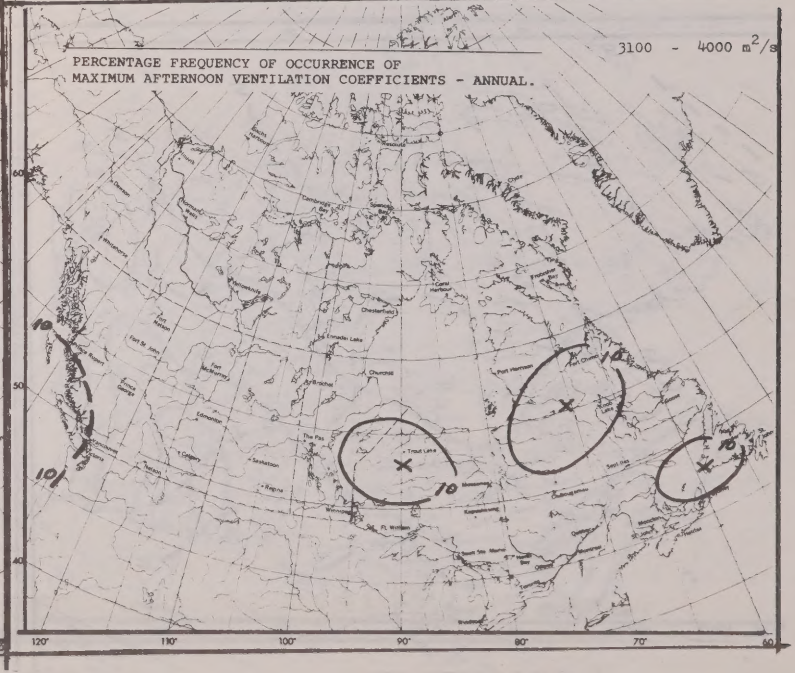

16.1 - 20.0 m/s
120°
110°
100°
90°
60°
50°
40°


20.1 + m/s
120°
110°
100°
90°
80°
70°
60°
50°
40°

APPENDIX A.III

MAXIMUM AFTERNOON
VENTILATION COEFFICIENTS





PERCENTAGE FREQUENCY OF OCCURRENCE OF
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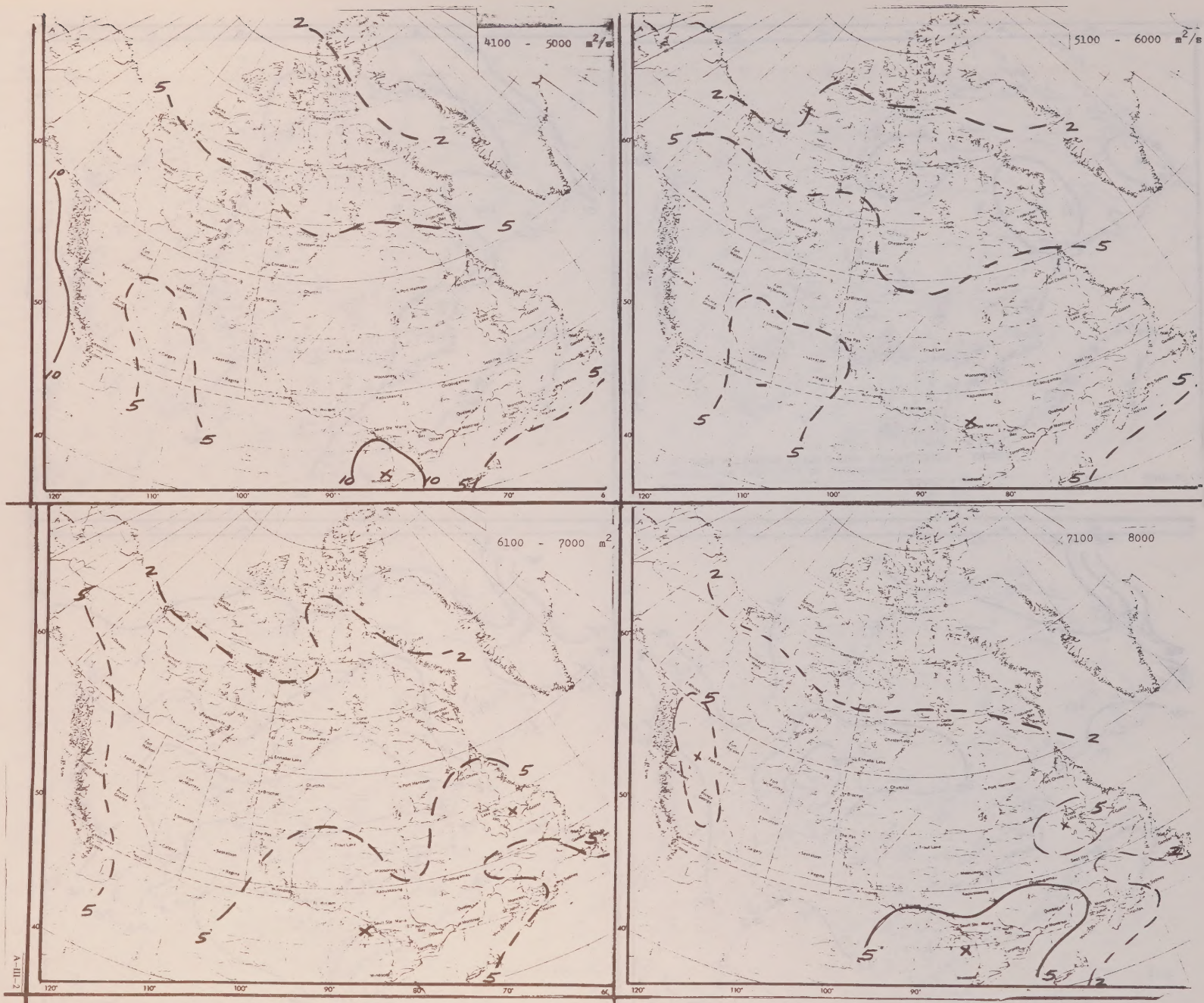

A-III-2

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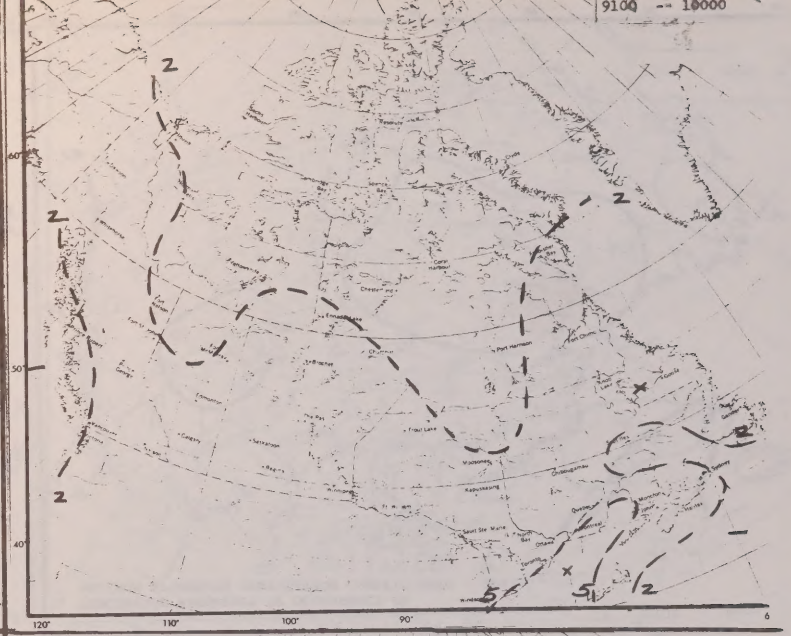
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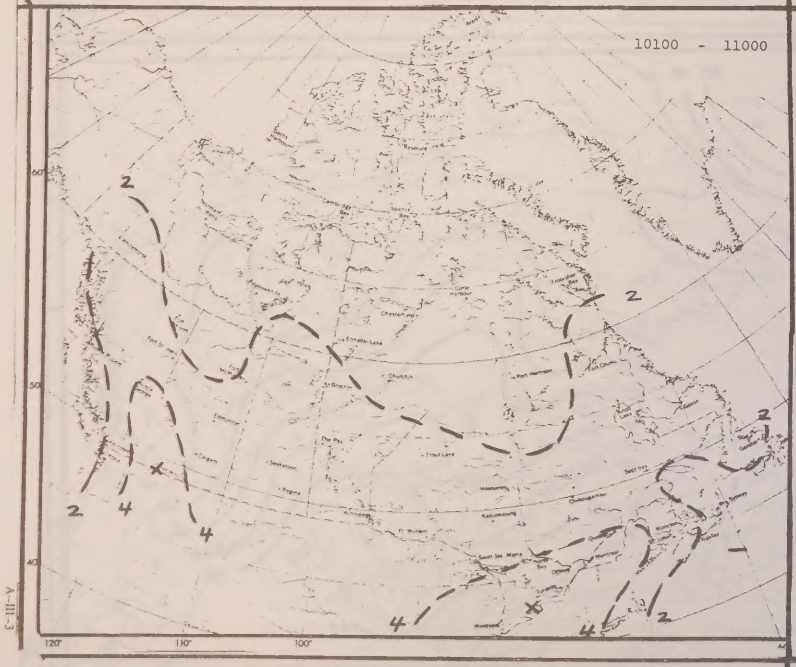
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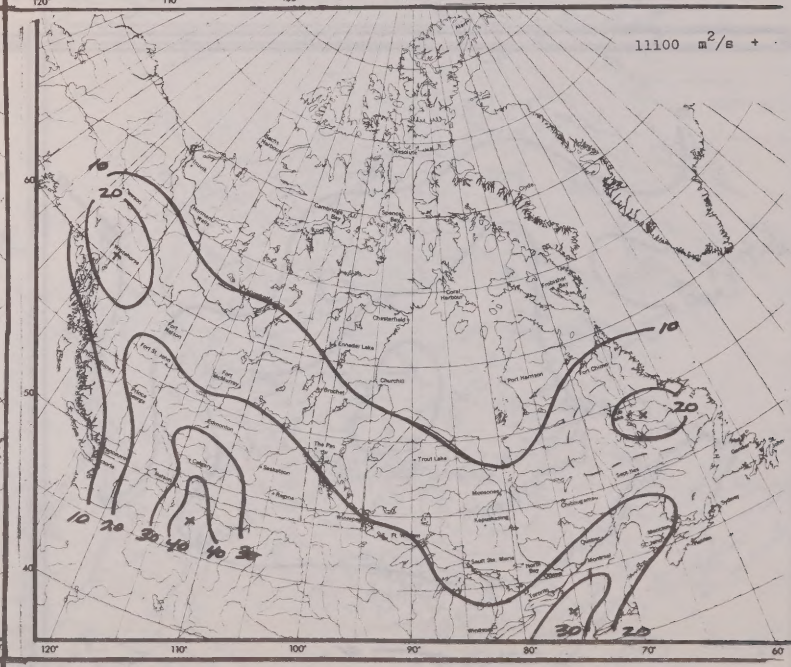
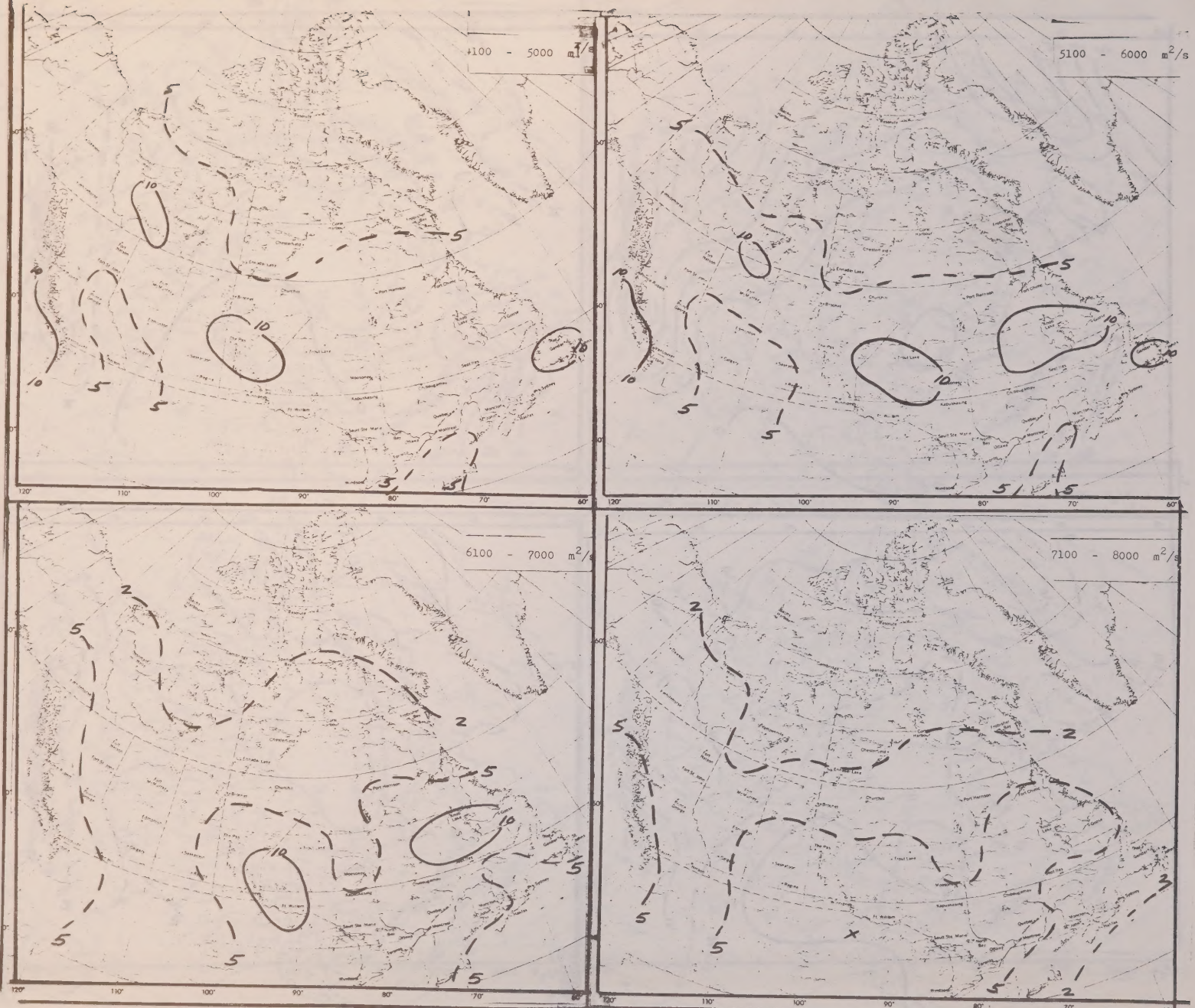
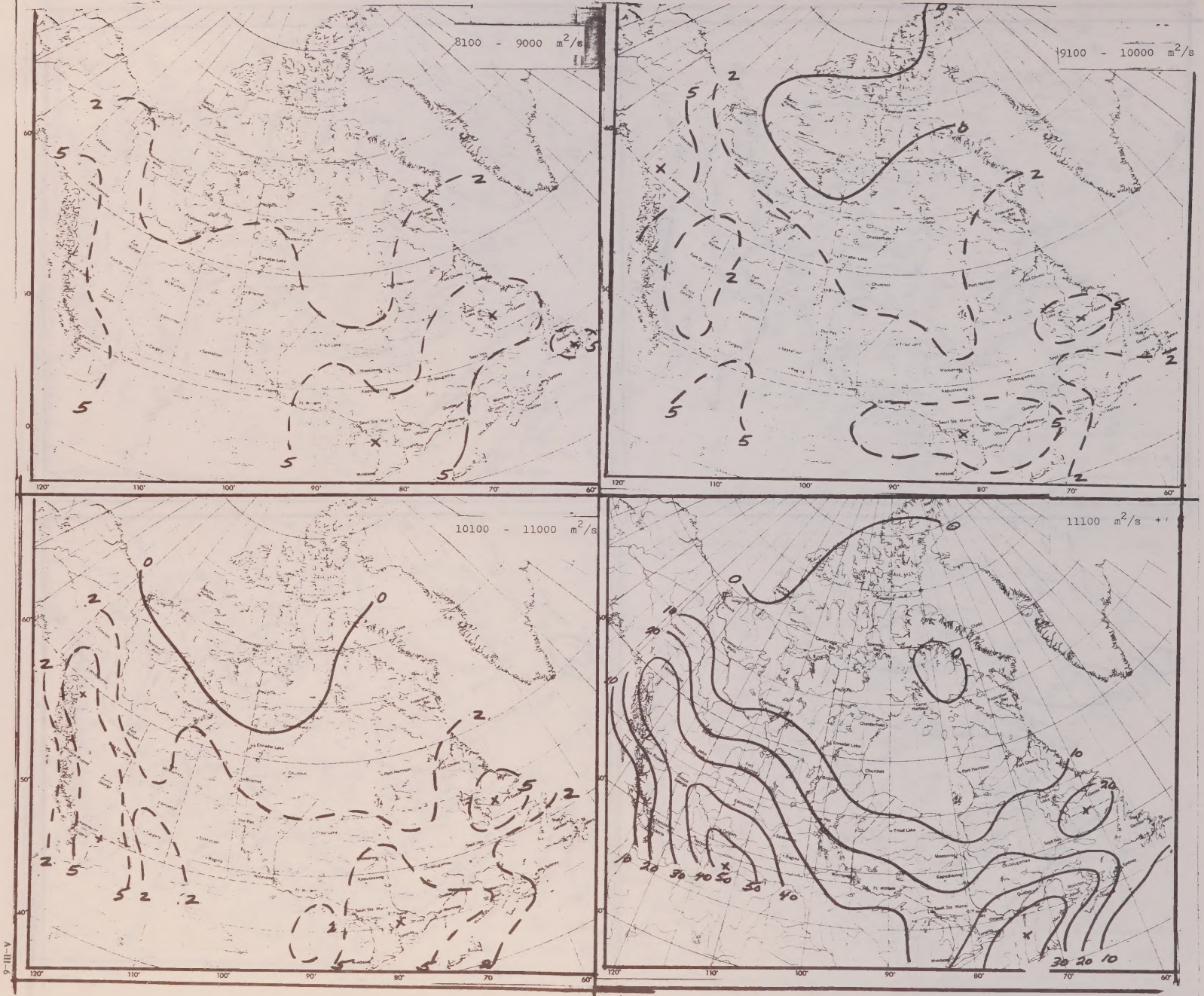

11100 m²/s²

0.0 - 1000 m²/s
1100 - 2000 m²/s
2100 - 3000 m²/s
3100 - 4000
PERCENTAGE FREQUENCY OF OCCURRENCE OF
MAXIMUM AFTERNOON VENTILATION COEFFICIENTS - SPRING.



A-III-52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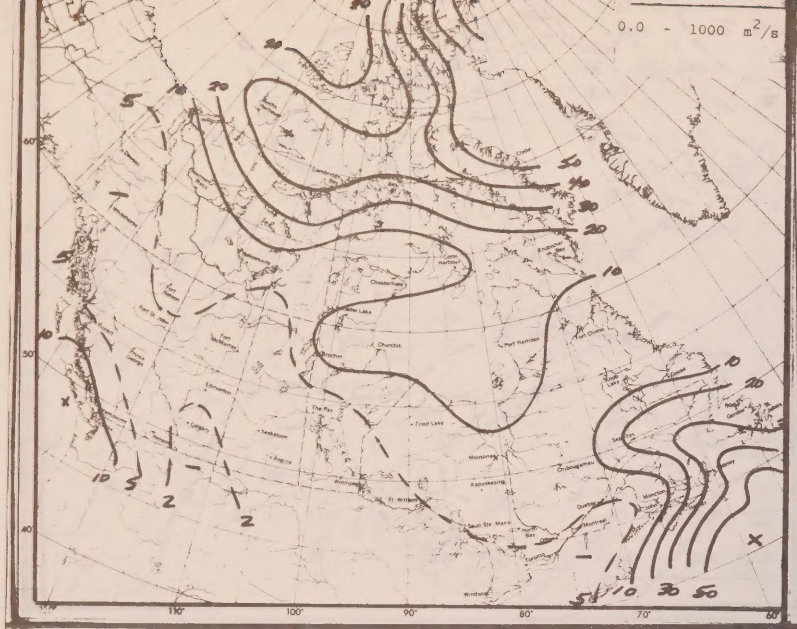
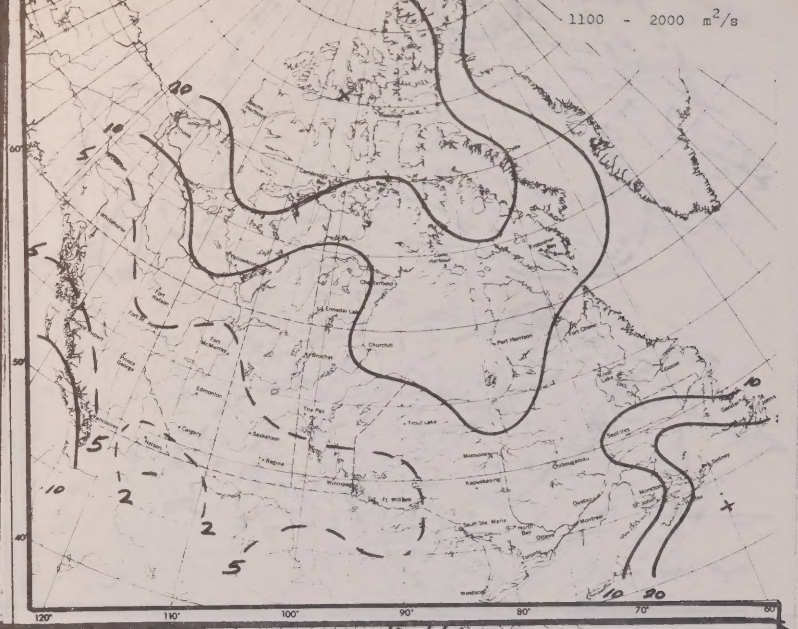
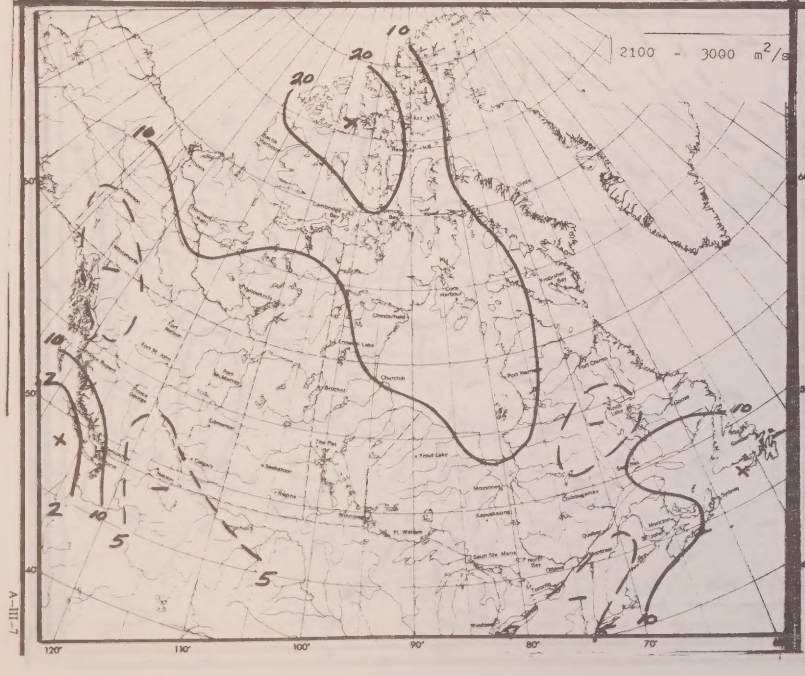
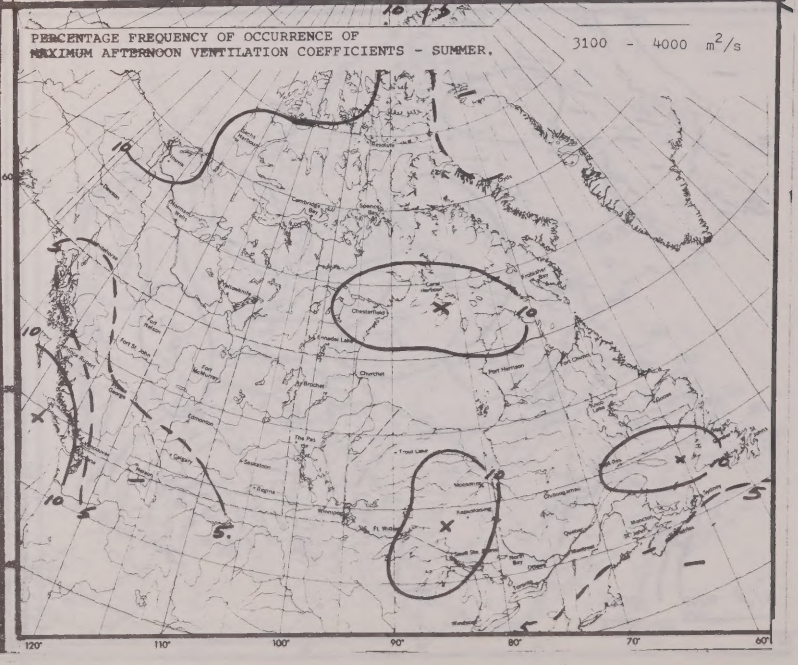
9100 - 10000 m²/s
10100 - 11000 m²/s
11100 m²/s +
120°
110°
100°
90°
80°
70°
60°
50°
40°
30°
0
2
5
10
20
30
40
50







PERCENTAGE FREQUENCY OF OCCURRENCE OF
MAXIMUM AFTERNOON VENTILATION COEFFICIENTS - SUMMER,



4100 - 5000 m²/s
120°
110°
100°
90°
80°
60°
50°
40°

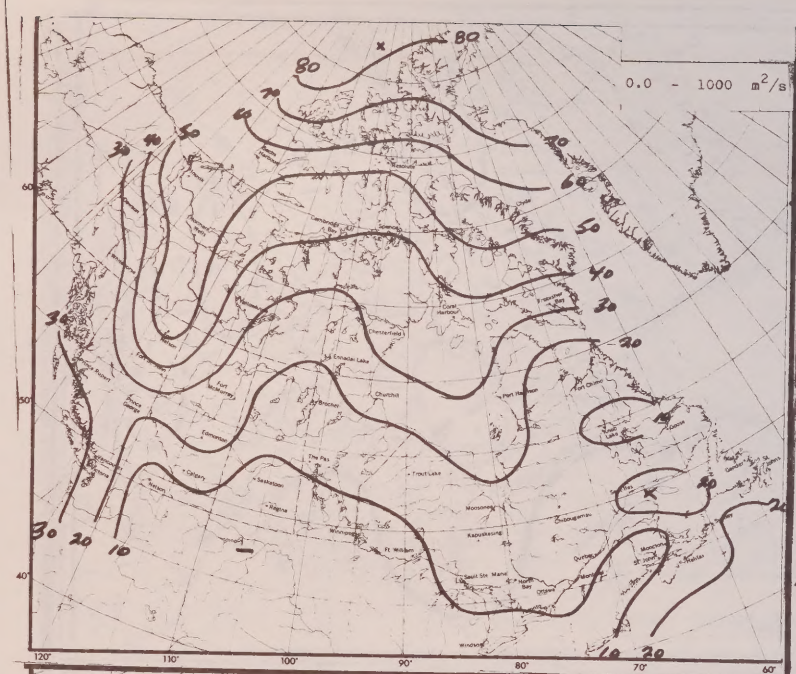
5100 - 6000 m²/s
120°
110°
100°
90°
80°
60°
50°
40°

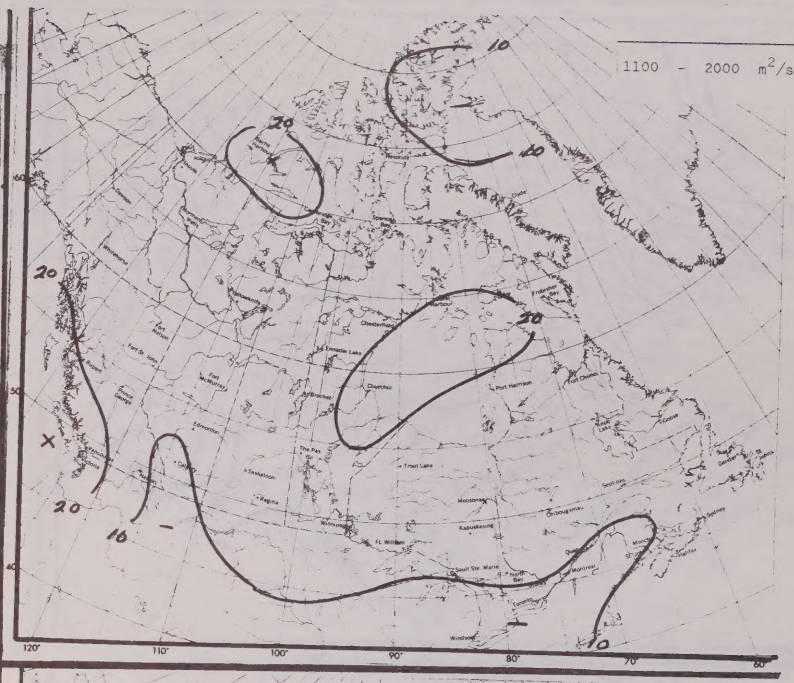
5100 - 7000 m²/s
120°
110°
100°
90°
80°
60°
50°
40°

7100 - 8000 m²/s
120°
110°
100°
90°
80°
60°
50°
40°

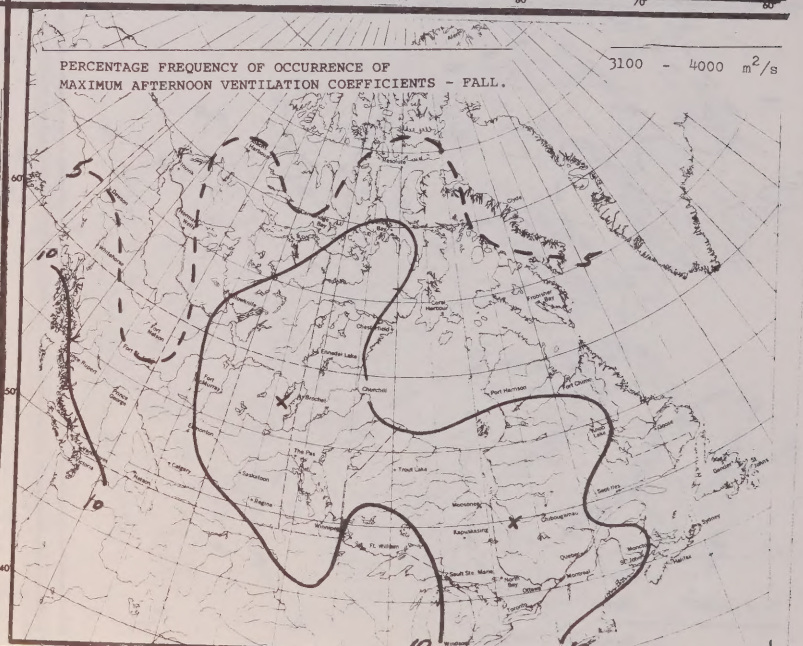
A-III-8

8100 - 9000 m²/s
9100 - 10000 m²/s
10100 - 11000 m²/s
11100 m²/s +

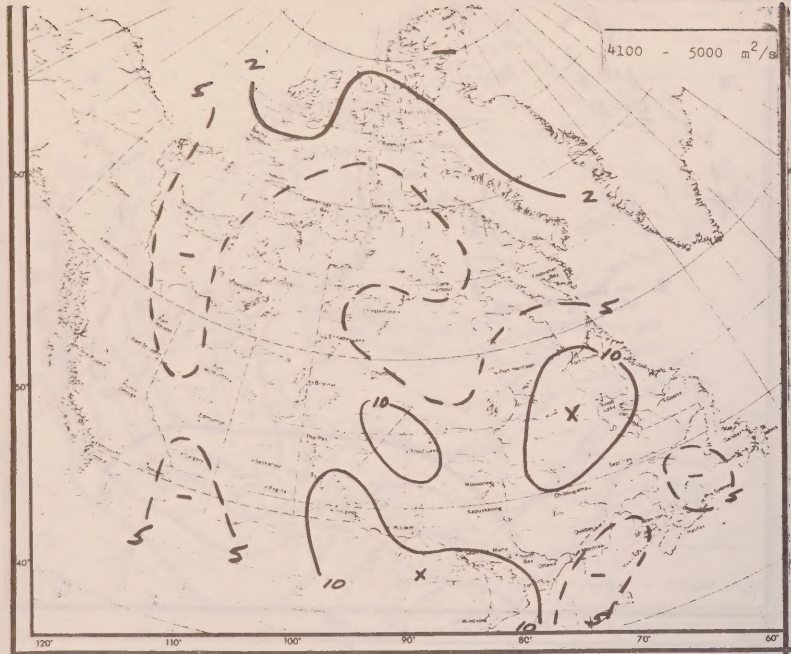




PERCENTAGE FREQUENCY OF OCCURRENCE OF
MAXIMUM AFTERNOON VENTILATION COEFFICIENTS - FALL.

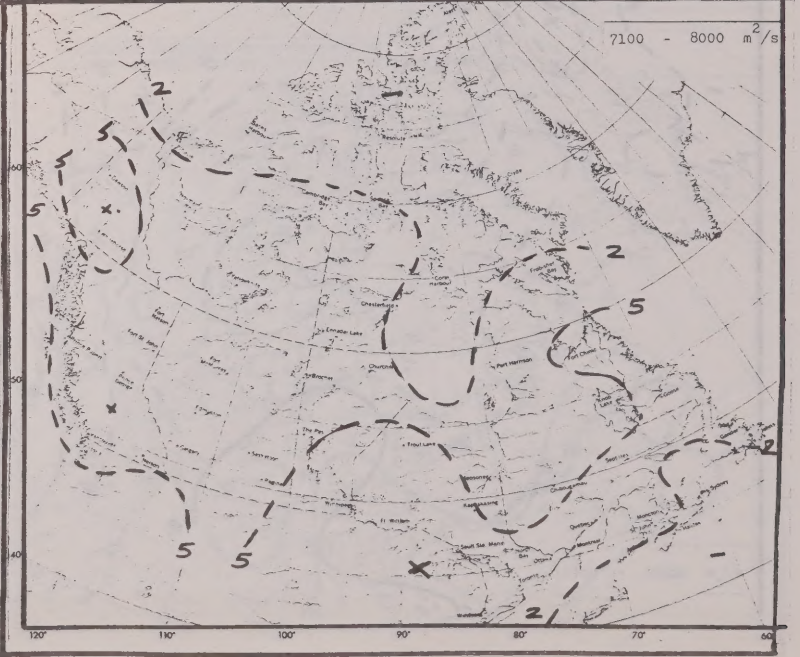


A-III-10


4100 - 5000 m²/s
120°
110°
100°
90°
80°
70°
60°
60°
50°
40°

5100 - 6000 m²/s
120°
110°
100°
90°
80°
70°
60°
60°
50°
40°

6100 - 7000 m²/s
120°
110°
100°
90°
80°
70°
60°
60°
50°
40°


7100 - 8000 m²/s
120°
110°
100°
90°
80°
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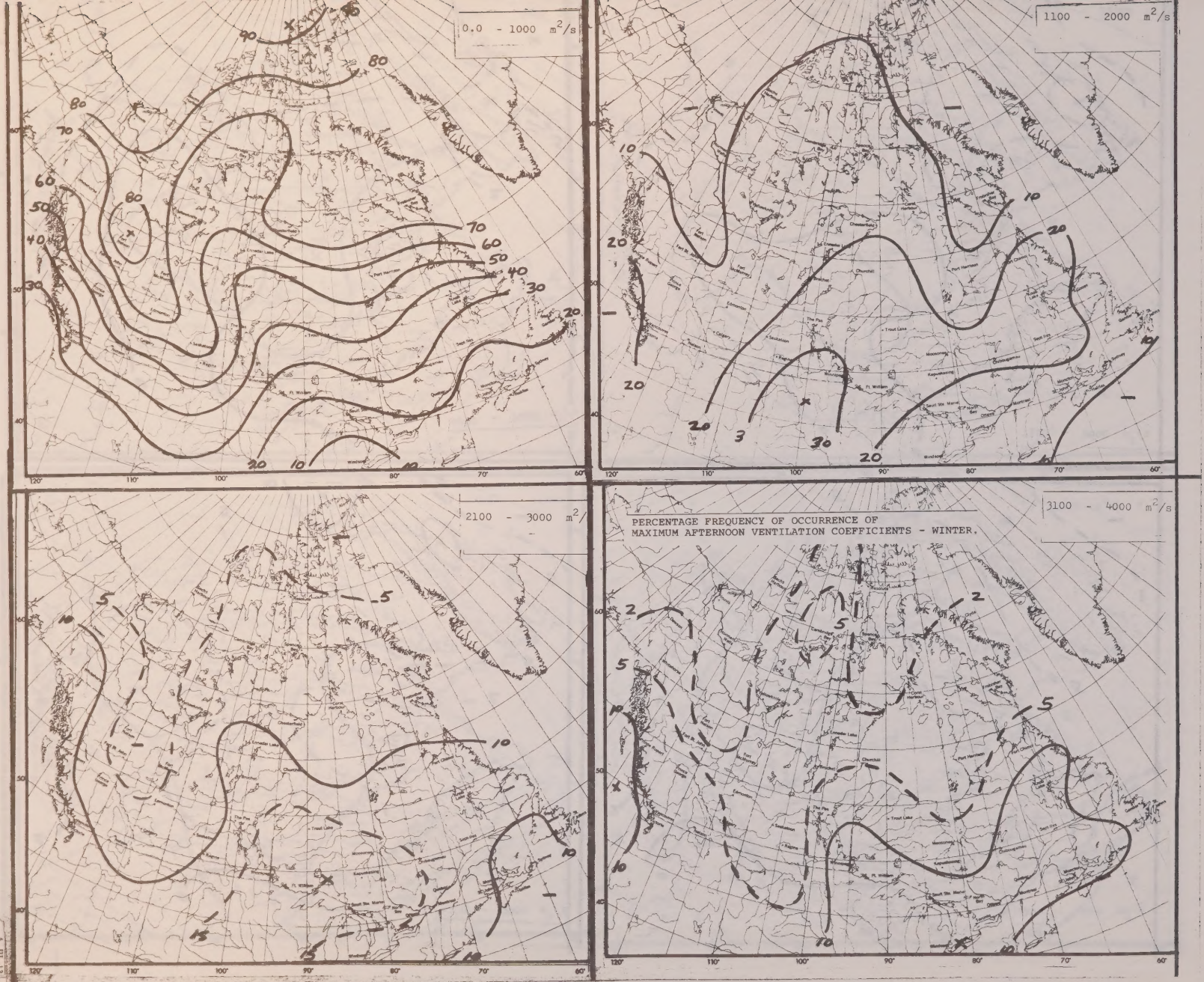
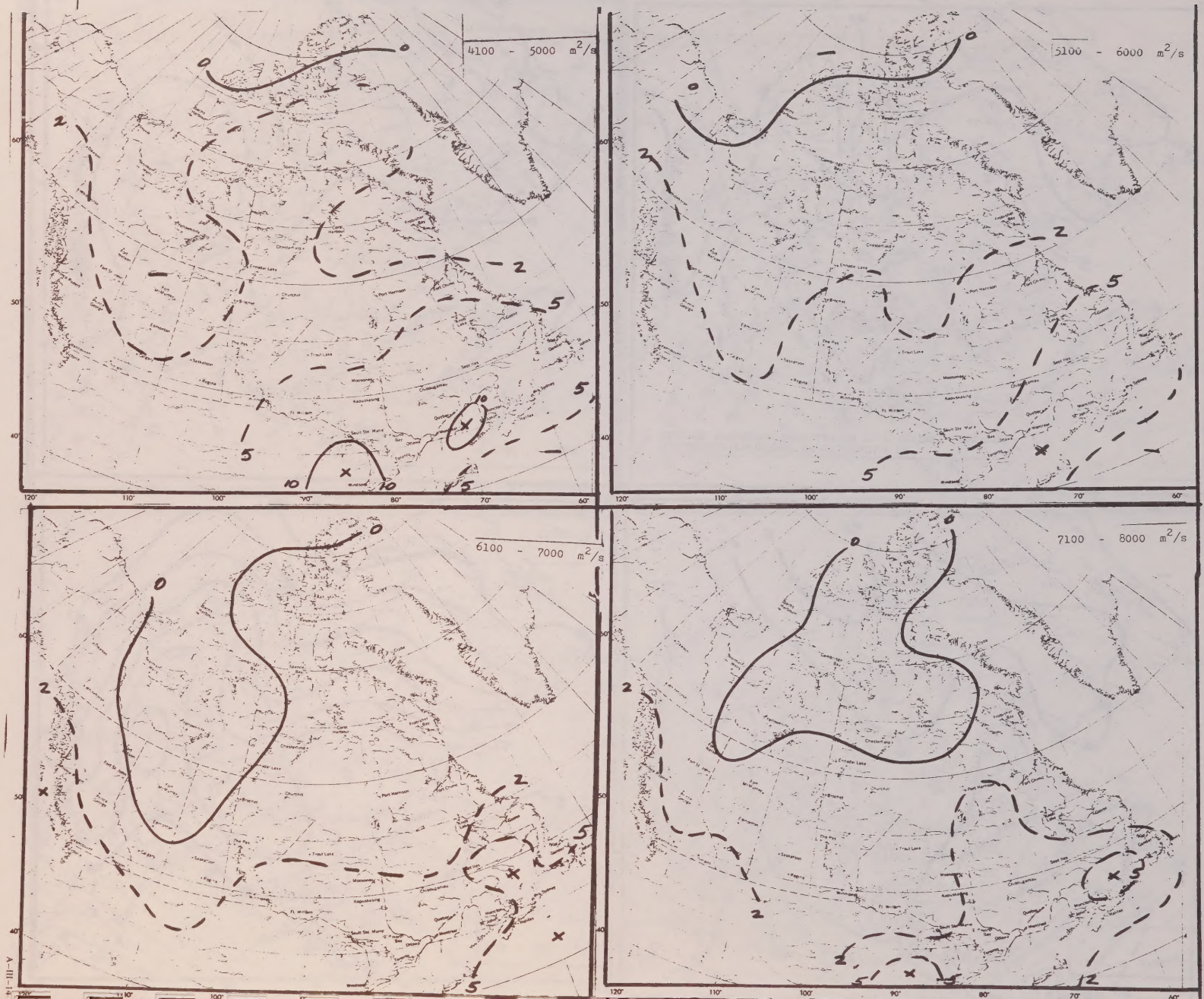
60°
60°
50°
40°

8100 - 9000 m²/s
9100 - 10000 m²/s
10100 - 11000 m²/s
11100 m²/s +


0.0 - 1000 m²/s
1100 - 2000 m²/s
2100 - 3000 m²/s
3100 - 4000 m²/s
PERCENTAGE FREQUENCY OF OCCURRENCE OF
MAXIMUM AFTERNOON VENTILATION COEFFICIENTS - WINTER.


4100 - 5000 m²/s
5100 - 6000 m²/s
6100 - 7000 m²/s
7100 - 8000 m²/s

8100 - 9000 m²/s
0
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X
120°
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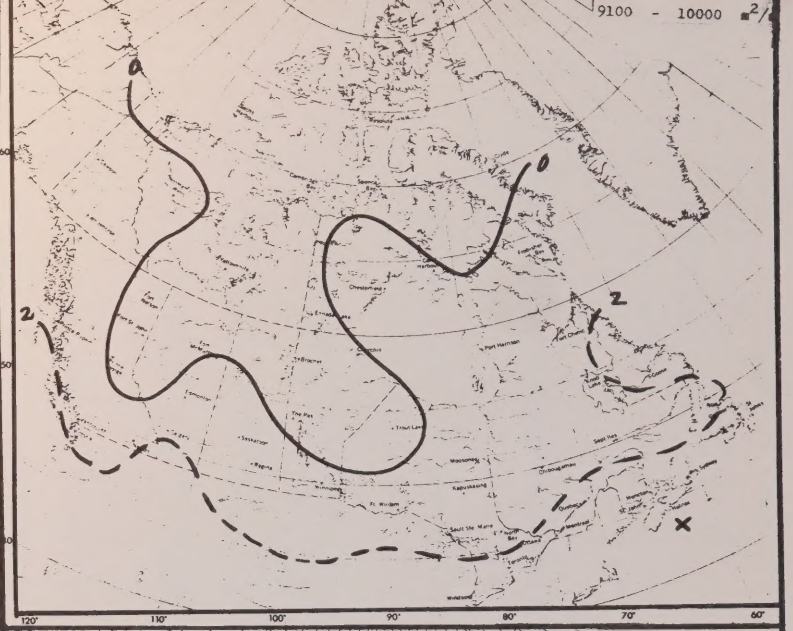
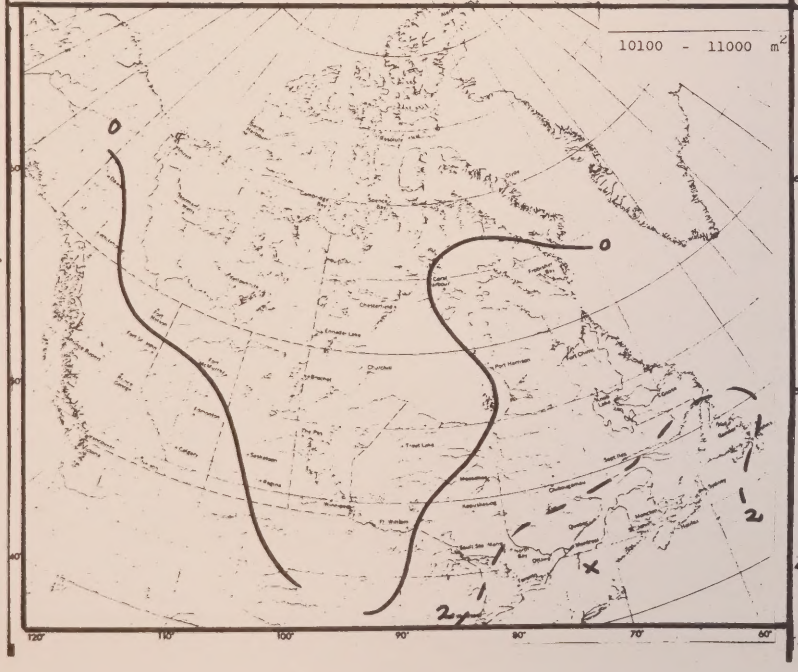
100°
90°
80°
70°
60°


9100 - 10000 m²/
0
0
2
2
X
120°
110°
100°
90°
80°
70°
60°


10100 - 11000 m²
0
0
2
2
X
120°
110°
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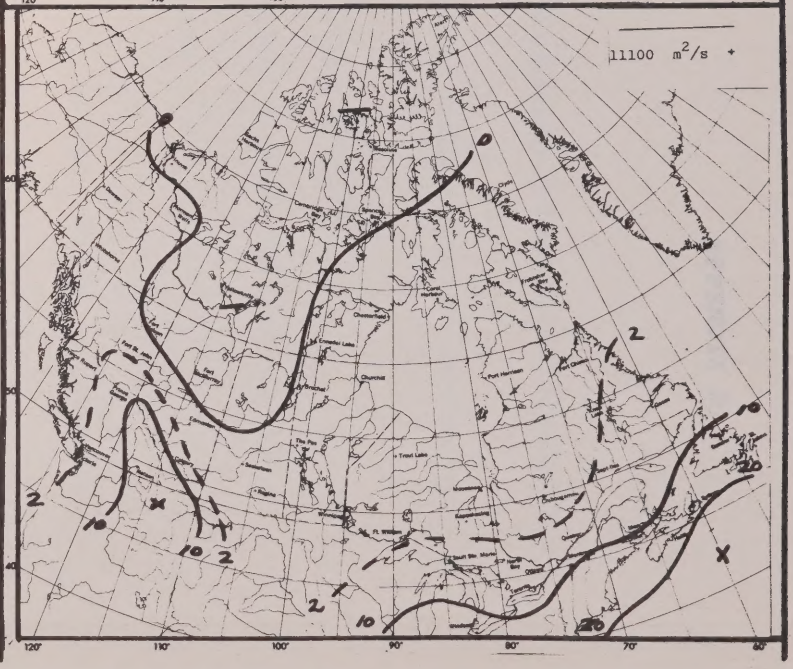
70°
60°


11100 m²/s +
0
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2
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20
X
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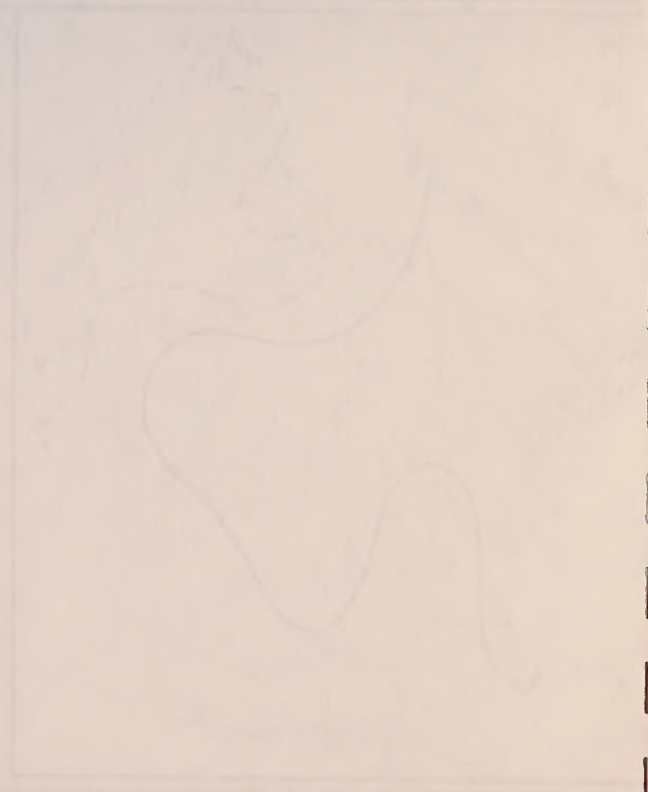


APPENDIX B

APPENDIX B

Regional Frequency Distributions of Mixing Depth Parameters

Seasonal and Annual Percentage Frequencies of Occurrence of:

1. Maximum (Afternoon) Mixing Heights (Tables 1.1 to 12.1)
2. Mean Transport Wind Speed Through the Mixed Layer (Tables 1.2 to 12.2)
3. Ventilation Coefficients (Tables 1.3 to 12.3)

are averaged over each of the twelve regions to provide a qualitative regional and seasonal comparison of the mixing depth statistics across Canada.

APPENDIX B - TABLES 1

MAXIMUM AFTERNOON
MIXING HEIGHTS

Table 1.1

PACIFIC REGION

Mixing Heights ($m \times 10^2$)	Percentage Frequencies (Mean)				
	Spring	Summer	Fall	Winter	Annual
0 - 2.0	4.1	3.4	22.1	18.6	12.1
2.1 - 4.0	7.8	11.8	32.7	40.1	23.1
4.1 - 6.0	13.3	24.4	21.6	21.8	20.3
6.1 - 8.0	20.0	26.4	12.2	12.5	17.8
8.1 - 10.0	15.2	12.6	6.5	5.1	9.9
10.1 - 12.0	14.2	11.3	3.7	.9	7.5
12.1 - 14.0	11.9	3.6	.3	.7	4.1
14.1 - 16.0	6.9	3.6	.8	0	2.8
16.1 - 18.0	3.9	2.5	0	.3	1.7
18.1 - 20.0	1.6	.3	0	0	.6
20.1 +	1.1	0	0	0	.3

Table 2.1

ROCKIES REGION

Mixing Heights ($m \times 10^2$)	Percentage Frequencies (Mean)				
	Spring	Summer	Fall	Winter	Annual
0 - 2.0	2.9	1.2	11.5	35.9	12.9
2.1 - 4.0	5.2	2.0	20.1	36.1	15.9
4.1 - 6.0	5.4	2.3	14.3	14.7	9.2
6.1 - 8.0	7.1	3.7	11.2	8.0	7.5
8.1 - 10.0	5.9	3.1	8.1	1.9	4.8
10.1 - 12.0	7.9	4.2	8.2	2.3	5.7
12.1 - 14.0	8.5	4.5	6.2	.5	4.9
14.1 - 16.0	6.7	7.4	6.0	.4	5.1
16.1 - 18.0	9.6	8.9	5.1	.2	6.0
18.1 - 20.0	8.7	9.4	3.4	0	5.4
20.1 +	32.3	53.4	6.0	0	22.9

Table 3.1

LEE OF THE ROCKIES REGION

Mixing Heights ($m \times 10^2$)	Percentage Frequencies (Mean)				
	Spring	Summer	Fall	Winter	Annual
0 - 2.0	5.2	1.9	9.8	37.2	13.5
2.1 - 4.0	9.7	2.3	13.7	36.7	15.6
4.1 - 6.0	8.7	3.4	11.7	11.4	15.6
6.1 - 8.0	6.6	5.1	9.9	6.3	7.0
8.1 - 10.0	5.2	3.7	8.3	2.5	5.0
10.1 - 12.0	6.6	5.2	7.9	1.4	5.3
12.1 - 14.0	4.6	4.4	7.3	1.4	4.4
14.1 - 16.0	4.9	6.4	7.0	.6	4.7
16.1 - 18.0	5.6	5.1	5.0	.5	4.1
18.1 - 20.0	4.8	6.8	5.8	.8	4.6
20.1 +	38.3	55.7	13.7	1.1	27.2

Table 4.1

PRAIRIES REGION

Mixing Heights ($m \times 10^2$)	Percentage Frequencies (Mean)				
	Spring	Summer	Fall	Winter	Annual
0 - 2.0	5.4	1.7	8.4	23.8	9.8
2.1 - 4.0	11.8	5.6	15.9	46.8	20.0
4.1 - 6.0	14.5	7.4	16.3	21.0	14.8
6.1 - 8.0	13.0	9.8	15.1	6.3	11.1
8.1 - 10.0	9.9	8.2	11.2	1.5	7.7
10.1 - 12.0	8.6	8.1	8.0	.5	6.3
12.1 - 14.0	6.8	10.2	8.0	.1	6.3
14.1 - 16.0	5.5	8.9	4.7	0	4.8
16.1 - 18.0	4.8	7.4	4.4	0	4.2
18.1 - 20.0	4.4	6.8	2.9	0	3.5
20.1 +	15.8	26.1	5.1	0	11.8

Table 5.1

GREAT LAKES REGION

Mixing Heights ($m \times 10^2$)	Percentage Frequencies (Mean)				
	Spring	Summer	Fall	Winter	Annual
0 - 2.0	4.9	2.4	6.3	11.1	6.2
2.1 - 4.0	8.7	4.8	10.9	26.7	12.8
4.1 - 6.0	10.0	5.9	13.5	27.8	14.3
6.1 - 8.0	10.4	9.2	14.7	15.3	12.4
8.1 - 10.0	11.3	9.0	13.5	11.6	11.4
10.1 - 12.0	10.2	10.0	12.0	3.9	9.0
12.1 - 14.0	9.3	11.7	10.8	2.3	8.5
14.1 - 16.0	8.0	11.9	7.3	.8	7.0
16.1 - 18.0	7.4	9.7	5.3	.4	5.7
18.1 - 20.0	6.1	9.3	3.2	.1	4.7
20.1 +	13.8	15.3	2.4	0	7.9

Table 6.1
APPALACHIAN REGION

Mixing Heights ($m \times 10^2$)	Percentage Frequencies (Mean)				
	Spring	Summer	Fall	Winter	Annual
0 - 2.0	2.8	1.1	4.5	8.7	4.3
2.1 - 4.0	6.9	3.8	10.5	22.6	11.0
4.1 - 6.0	8.9	4.5	12.9	22.6	12.2
6.1 - 8.0	9.0	6.5	10.8	17.6	11.0
8.1 - 10.0	8.8	6.7	10.3	13.3	9.8
10.1 - 12.0	9.2	8.9	10.8	7.5	9.1
12.1 - 14.0	7.5	11.4	13.8	3.8	9.1
14.1 - 16.0	10.5	9.3	10.4	1.7	8.0
16.1 - 18.0	8.6	11.8	6.8	1.0	7.1
18.1 - 20.0	7.6	12.0	4.6	1.3	6.4
20.1 +	20.9	24.7	4.8	.5	12.7

Table 7.1

ATLANTIC REGION

Mixing Heights ($m \times 10^2$)	Percentage Frequencies (Mean)				
	Spring	Summer	Fall	Winter	Annual
0 - 2.0	17.3	29.2	16.7	20.8	21.0
2.1 - 4.0	15.1	19.5	17.4	17.7	17.3
4.1 - 6.0	17.8	14.7	15.9	20.6	17.3
6.1 - 8.0	14.5	11.7	12.6	14.8	13.4
8.1 - 10.0	11.9	7.6	11.3	12.3	10.8
10.1 - 12.0	9.2	5.7	12.0	7.6	8.6
12.1 - 14.0	3.8	3.6	6.0	3.7	4.3
14.1 - 16.0	5.2	3.4	5.4	1.5	3.9
16.1 - 18.0	2.0	1.9	1.4	.8	1.5
18.1 - 20.0	1.8	1.3	.9	.4	1.1
20.1 +	1.7	1.6	.7	0	1.0

Table 8.1

QUEBEC - LABRADOR REGION

Mixing Heights ($m \times 10^2$)	Percentage Frequencies (Mean)				
	Spring	Summer	Fall	Winter	Annual
0 - 2.0	3.2	2.1	8.5	18.8	8.2
2.1 - 4.0	8.3	6.3	15.8	37.5	17.0
4.1 - 6.0	13.7	7.7	21.0	26.3	17.1
6.1 - 8.0	14.7	5.7	14.1	9.3	11.0
8.1 - 10.0	14.8	8.3	11.4	5.7	10.1
10.1 - 12.0	13.9	8.2	7.7	1.9	7.9
12.1 - 14.0	9.5	9.8	7.6	.5	6.9
14.1 - 16.0	9.1	11.4	4.5	0	6.3
16.1 - 18.0	3.8	11.6	3.8	0	4.8
18.1 - 20.0	4.3	6.0	2.9	0	3.3
20.1 +	5.5	23.2	3.0	0	7.9

Table 9.1

MACKENZIE VALLEY REGION

Mixing Heights ($m \times 10^2$)	Percentage Frequencies (Mean)				
	Spring	Summer	Fall	Winter	Annual
0 - 2.0	9.7	2.5	28.9	59.3	25.1
2.1 - 4.0	17.4	6.1	25.7	31.0	20.1
4.1 - 6.0	15.3	7.8	12.8	7.6	10.9
6.1 - 8.0	13.4	7.9	10.0	1.8	8.3
8.1 - 10.0	10.3	7.8	8.0	.3	6.6
10.1 - 12.0	7.5	7.3	5.2	0	5.0
12.1 - 14.0	4.7	8.0	3.2	0	4.0
14.1 - 16.0	4.1	8.1	1.7	0	3.5
16.1 - 18.0	3.7	8.8	1.6	0	3.5
18.1 - 20.0	2.3	8.8	1.1	0	3.1
20.1 +	11.6	26.9	1.8	0	10.1

Table 10.1

HUDSON BAY REGION

Mixing Heights ($m \times 10^2$)	Percentage Frequencies (Mean)				
	Spring	Summer	Fall	Winter	Annual
0 - 2.0	18.7	8.6	24.5	51.7	25.9
2.1 - 4.0	29.5	14.2	22.4	31.0	24.3
4.1 - 6.0	20.2	16.1	17.7	11.6	16.4
6.1 - 8.0	11.0	11.9	13.5	3.8	10.0
8.1 - 10.0	6.6	11.8	8.6	1.2	7.1
10.1 - 12.0	4.5	9.2	5.7	.4	5.0
12.1 - 14.0	3.2	8.3	3.1	.2	3.7
14.1 - 16.0	1.9	6.5	2.4	0	2.7
16.1 - 18.0	1.4	4.2	1.0	0	1.7
18.1 - 20.0	.9	3.1	.8	0	1.2
20.1 +	2.1	6.3	.3	0	2.2

Table 11.1

BAFFIN REGION

Mixing Heights ($m \times 10^2$)	Percentage Frequencies (Mean)				
	Spring	Summer	Fall	Winter	Annual
0 - 2.0	17.3	13.1	29.7	62.2	30.6
2.1 - 4.0	28.4	18.1	23.9	25.8	24.1
4.1 - 6.0	24.6	15.2	16.5	9.1	16.4
6.1 - 8.0	13.4	12.0	11.0	2.0	9.6
8.1 - 10.0	7.1	10.6	7.4	.6	6.4
10.1 - 12.0	4.4	6.1	4.0	.3	3.7
12.1 - 14.0	2.5	6.3	3.4	0	3.1
14.1 - 16.0	1.4	8.2	2.3	0	3.0
16.1 - 18.0	.4	3.1	1.0	0	1.1
18.1 - 20.0	.2	3.2	.6	0	1.0
20.1 +	.3	4.3	.3	0	1.2

Table 12.1

HIGH ARCTIC REGION

Mixing Heights ($m \times 10^2$)	Percentage Frequencies (Mean)				
	Spring	Summer	Fall	Winter	Annual
0 - 2.0	55.2	30.6	60.7	83.8	57.6
2.1 - 4.0	28.1	29.5	22.6	12.7	23.2
4.1 - 6.0	9.9	20.0	10.2	3.1	10.8
6.1 - 8.0	4.5	9.1	3.5	.4	4.4
8.1 - 10.0	1.6	5.0	1.9	0	2.1
10.1 - 12.0	.4	2.8	1.1	0	1.1
12.1 - 14.0	.3	1.3	0	0	.5
14.1 - 16.0	0	.9	0	0	.2
16.1 - 18.0	0	.3	0	0	.1
18.1 - 20.0	0	.2	0	0	0
20.1 +	0	.3	0	0	0

APPENDIX B - TABLES 2

MEAN WIND SPEEDS
THROUGH THE MIXING LAYER

Table 1.2
PACIFIC REGION

Mean Wind Speed ($m\ sec^{-1}$)	Percentage Frequencies (Mean)				
	Spring	Summer	Fall	Winter	Annual
0 - 4.0	35.8	46.3	45.4	40.1	41.9
4.1 - 8.0	44.0	45.2	37.8	33.3	40.1
8.1 - 12.0	15.0	8.2	11.9	15.2	12.6
12.1 - 16.0	3.9	.3	4.2	9.0	4.4
16.1 - 20.0	1.0	0	.5	1.2	.7
20.1 +	.3	0	0	1.2	.4

Table 2.2
ROCKIES REGION

Mean Wind Speed ($m\ sec^{-1}$)	Percentage Frequencies (Mean)				
	Spring	Summer	Fall	Winter	Annual
0 - 4.0	30.2	37.2	37.2	53.2	39.5
4.1 - 8.0	47.8	50.6	41.2	30.5	42.5
8.1 - 12.0	18.6	11.2	17.2	12.6	14.9
12.1 - 16.0	3.1	.8	3.4	2.9	2.6
16.1 - 20.0	.4	.1	.9	.3	.5
20.1 +	0	0	.1	.3	.1

Table 3.2
LEE OF THE ROCKIES REGION

Mean Wind Speed ($m\ sec^{-1}$)	Percentage Frequencies (Mean)				
	Spring	Summer	Fall	Winter	Annual
0 - 4.0	21.7	21.5	20.5	47.6	27.8
4.1 - 8.0	40.9	49.8	45.1	30.8	41.7
8.1 - 12.0	26.6	22.3	22.4	12.6	21.0
12.1 - 16.0	8.7	5.6	8.9	6.5	7.4
16.1 - 20.0	2.2	.8	2.4	2.0	1.9
20.1 +	.3	0	.6	.5	.4

Table 4.2
PRAIRIES REGION

Mean Wind Speed ($m\ sec^{-1}$)	Percentage Frequencies (Mean)				
	Spring	Summer	Fall	Winter	Annual
0 - 4.0	17.3	18.4	23.5	44.8	26.0
4.1 - 8.0	42.2	49.0	41.9	39.7	43.2
8.1 - 12.0	30.7	25.8	25.3	11.5	23.3
12.1 - 16.0	8.2	6.2	7.7	3.5	6.4
16.1 - 20.0	1.3	.7	1.4	.6	1.0
20.1 +	.6	0	.6	0	.3

Table 5.2
GREAT LAKES REGION

Mean Wind Speed ($m\ sec^{-1}$)	Percentage Frequencies (Mean)				
	Spring	Summer	Fall	Winter	Annual
0 - 4.0	15.9	21.3	22.4	27.6	21.8
4.1 - 8.0	44.7	48.4	42.6	45.6	45.3
8.1 - 12.0	28.4	24.8	26.1	19.8	24.8
12.1 - 16.0	9.2	5.1	7.2	5.5	6.8
16.1 - 20.0	1.4	.4	1.7	1.2	1.2
20.1 +	.5	0	0	.3	.2

Table 6.2
APPALACHIAN REGION

Mean Wind Speed ($m\ sec^{-1}$)	Percentage Frequencies (Mean)				
	Spring	Summer	Fall	Winter	Annual
0 - 4.0	16.5	17.6	22.5	26.4	20.8
4.1 - 8.0	38.5	49.4	41.0	38.4	41.8
8.1 - 12.0	31.7	26.5	26.4	24.5	27.3
12.1 - 16.0	11.5	6.1	9.0	9.5	9.0
16.1 - 20.0	1.7	.6	1.0	1.2	1.1
20.1 +	.3	0	.2	.2	.2

Table 7.2
ATLANTIC REGION

Mean Wind Speed ($m\ sec^{-1}$)	Percentage Frequencies (Mean)				
	Spring	Summer	Fall	Winter	Annual
0 - 4.0	25.7	30.3	24.0	20.6	25.2
4.1 - 8.0	38.0	41.7	37.4	32.8	37.5
8.1 - 12.0	23.5	22.7	25.1	24.6	24.0
12.1 - 16.0	8.2	4.6	8.9	13.9	8.9
16.1 - 20.0	3.2	.9	2.5	5.6	3.1
20.1 +	1.3	.1	.9	2.3	1.2

Table 8.2
QUEBEC-LABRADOR REGION

Mean Wind Speed ($m\ sec^{-1}$)	Percentage Frequencies (Mean)				
	Spring	Summer	Fall	Winter	Annual
0 - 4.0	22.2	21.5	23.9	40.0	26.9
4.1 - 8.0	48.0	43.4	40.7	36.0	42.0
8.1 - 12.0	20.6	25.4	24.7	16.7	21.9
12.1 - 16.0	8.5	7.7	8.6	5.1	7.5
16.1 - 20.0	.8	2.0	1.8	2.0	1.7
20.1 +	.2	.2	.3	.5	.3

Table 9.2
MACKENZIE VALLEY REGION

Mean Wind Speed ($m\ sec^{-1}$)	Percentage Frequencies (Mean)				
	Spring	Summer	Fall	Winter	Annual
0 - 4.0	47.1	38.0	58.3	77.7	55.3
4.1 - 8.0	42.8	46.1	31.6	17.0	34.4
8.1 - 12.0	8.7	14.9	8.3	4.5	9.1
12.1 - 16.0	1.3	.8	1.4	.7	1.1
16.1 - 20.0	.2	.2	.4	.1	.2
20.1 +	0	0	0	0	0

Table 10.2
HUDSON BAY REGION

Mean Wind Speed ($m\ sec^{-1}$)	Percentage Frequencies (Mean)				
	Spring	Summer	Fall	Winter	Annual
0 - 4.0	22.1	18.7	23.4	35.3	24.8
4.1 - 8.0	42.8	47.4	39.3	39.0	42.3
8.1 - 12.0	23.8	24.0	23.0	16.5	21.8
12.1 - 16.0	8.1	7.4	11.2	6.6	8.3
16.1 - 20.0	2.3	2.1	2.2	1.8	2.1
20.1 +	.8	.3	1.0	.9	.8

Table 11.2
BAFFIN REGION

Mean Wind Speed
($m\ sec^{-1}$)

Percentage Frequencies (Mean)

	Spring	Summer	Fall	Winter	Annual
0 - 4.0	44.9	40.6	41.4	56.6	45.9
4.1 - 8.0	34.8	42.0	34.2	24.6	33.9
8.1 - 12.0	13.9	13.1	17.1	11.4	13.9
12.1 - 16.0	4.9	3.8	5.4	4.9	4.8
16.1 - 20.0	1.2	.4	1.0	1.9	1.1
20.1 +	.4	.2	.9	.8	.6

Table 12.2
HIGH ARCTIC REGION

Mean Wind Speed ($m\ sec^{-1}$)	Percentage Frequencies (Mean)				
	Spring	Summer	Fall	Winter	Annual
0 - 4.0	45.9	35.9	44.2	49.5	43.9
4.1 - 8.0	32.5	45.0	33.3	33.1	36.0
8.1 - 12.0	14.0	15.0	14.5	12.6	14.0
12.1 - 16.0	5.5	3.5	6.0	3.7	4.7
16.1 - 20.0	1.5	.6	1.4	.7	1.1
20.1 +	.4	.3	.6	.5	.8

APPENDIX B - TABLES 3

MAXIMUM AFTERNOON
VENTILATION COEFFICIENTS

Table 1.3
PACIFIC REGION

Ventilation Coefficient (m^2/sec x 10^3)	Percentage Frequencies (Mean)				
	Spring	Summer	Fall	Winter	Annual
0 - 1.0	9.2	11.5	35.0	43.2	22.5
1.1 - 2.0	13.3	21.4	23.3	21.5	19.9
2.1 - 3.0	13.1	20.8	14.5	10.8	14.8
3.1 - 4.0	10.0	13.2	10.2	9.3	10.7
4.1 - 5.0	7.8	11.3	6.8	6.9	8.2
5.1 - 6.0	11.9	5.1	1.5	4.8	5.8
6.1 - 7.0	6.1	6.2	3.1	4.8	5.1
7.1 - 8.0	6.9	3.4	2.8	3.0	4.0
8.1 - 9.0	7.2	3.4	.8	1.8	3.3
9.1 - 10.0	2.8	1.1	.3	1.5	1.4
10.1 - 11.0	2.2	.5	.5	.3	.9
11.1 +	9.7	2.3	1.1	1.2	3.6

Table 2.3
ROCKIES REGION

Ventilation Coefficient ($m^2/sec \times 10^3$)	Percentage Frequencies (Mean)				
	Spring	Summer	Fall	Winter	Annual
0 - 1.0	5.5	2.9	20.9	53.7	20.8
1.1 - 2.0	6.2	3.1	14.3	14.6	9.6
2.1 - 3.0	5.8	3.5	11.0	12.1	8.1
3.1 - 4.0	6.9	4.3	8.8	5.9	6.5
4.1 - 5.0	6.8	5.6	7.6	3.7	5.9
5.1 - 6.0	6.5	6.7	5.5	2.9	5.4
6.1 - 7.0	6.3	5.6	4.8	1.5	4.6
7.1 - 8.0	4.1	8.1	4.4	1.4	4.5
8.1 - 9.0	6.3	6.4	4.2	.7	4.4
9.1 - 10.0	4.3	7.2	3.5	.5	3.9
10.1 - 11.0	6.4	6.7	1.8	.6	3.9
11.1 +	35.2	39.9	13.3	2.2	22.7

Table 3.3

LEE OF THE ROCKIES REGION

Ventilation Coefficient ($m^2/sec \times 10^3$)	Percentage Frequencies (Mean)				
	Spring	Summer	Fall	Winter	Annual
0 - 1.0	8.6	1.9	12.5	49.7	18.2
1.1 - 2.0	7.9	3.0	10.8	20.0	10.4
2.1 - 3.0	6.8	4.7	8.1	8.5	7.0
3.1 - 4.0	5.8	5.5	8.0	5.2	6.1
4.1 - 5.0	4.5	4.2	5.1	2.4	4.1
5.1 - 6.0	3.6	4.6	5.9	2.4	4.1
6.1 - 7.0	3.6	3.3	5.6	1.0	3.4
7.1 - 8.0	4.9	4.4	3.5	1.9	3.7
8.1 - 9.0	3.5	4.5	3.3	1.1	3.1
9.1 - 10.0	4.0	4.8	3.5	1.7	3.5
10.1 - 11.0	1.9	3.8	3.6	1.0	2.6
11.1 +	45.1	55.4	30.0	5.4	34.0

Table 4.3
PRAIRIES REGION

Ventilation Coefficient ($m^2/sec \times 10^3$)	Percentage Frequencies (Mean)				
	Spring	Summer	Fall	Winter	Annual
0 - 1.0	6.1	1.8	49.8	40.9	14.7
1.1 - 2.0	11.7	6.0	15.4	26.8	15.0
2.1 - 3.0	7.5	6.4	11.8	12.5	9.6
3.1 - 4.0	8.5	7.2	10.6	9.1	8.9
4.1 - 5.0	9.2	7.6	8.2	3.9	7.2
5.1 - 6.0	6.7	6.4	7.0	3.3	5.9
6.1 - 7.0	6.5	6.7	3.7	1.2	4.5
7.1 - 8.0	5.3	6.7	5.1	1.1	4.6
8.1 - 9.0	2.2	5.0	4.3	.6	3.0
9.1 - 10.0	3.2	5.3	2.4	.2	2.8
10.1 - 11.0	3.1	3.9	3.9	0	2.7
11.1 +	30.0	37.2	17.9	.4	21.4

Table 5.3

GREAT LAKES REGION

Ventilation Coefficient (m^2/sec x 10^3)	Percentage Frequencies (Mean)				
	Spring	Summer	Fall	Winter	Annual
0 - 1.0	6.1	4.0	9.4	20.1	9.9
1.1 - 2.0	7.2	4.9	10.0	20.5	10.7
2.1 - 3.0	7.2	6.7	9.4	15.3	9.7
3.1 - 4.0	7.4	7.6	9.9	13.0	9.5
4.1 - 5.0	7.8	7.6	9.1	8.5	8.3
5.1 - 6.0	7.2	8.2	7.2	5.3	7.0
6.1 - 7.0	7.5	7.3	7.5	3.9	6.6
7.1 - 8.0	6.1	6.8	6.4	2.7	5.5
8.1 - 9.0	5.3	6.0	4.5	2.9	4.7
9.1 - 10.0	4.7	5.3	3.5	1.9	3.9
10.1 - 11.0	4.4	4.7	3.7	1.3	3.5
11.1 +	29.3	31.2	19.4	5.0	21.2

Table 6.3

APPALACHIANS REGION

Ventilation Coefficient ($m^2/sec \times 10^3$)	Percentage Frequencies (Mean)				
	Spring	Summer	Fall	Winter	Annual
0 - 1.0	4.3	2.8	8.0	16.5	7.9
1.1 - 2.0	4.8	3.3	8.7	15.6	8.1
2.1 - 3.0	6.1	3.4	8.3	14.2	8.0
3.1 - 4.0	6.7	4.9	10.4	10.6	8.2
4.1 - 5.0	5.2	6.6	6.5	7.4	6.4
5.1 - 6.0	5.5	6.8	6.1	7.3	6.4
6.1 - 7.0	6.2	5.6	6.1	4.9	5.7
7.1 - 8.0	5.5	5.1	4.3	4.0	4.7
8.1 - 9.0	5.1	6.1	7.1	3.9	5.6
9.1 - 10.0	5.8	6.0	4.9	3.1	5.0
10.1 - 11.0	4.6	7.2	4.9	2.2	4.7
11.1 +	40.4	42.3	24.7	10.8	29.6

Table 7.3

ATLANTIC REGION

Ventilation Coefficient ($m^2/sec \times 10^3$)	Percentage Frequencies (Mean)				
	Spring	Summer	Fall	Winter	Annual
0 - 1.0	19.5	31.6	20.1	20.7	23.0
1.1 - 2.0	14.0	17.6	13.1	16.1	15.2
2.1 - 3.0	10.5	12.1	11.3	11.2	11.3
3.1 - 4.0	9.2	8.8	9.0	9.2	9.1
4.1 - 5.0	8.2	5.7	6.3	6.9	6.8
5.1 - 6.0	8.4	5.2	6.6	6.0	6.6
6.1 - 7.0	5.8	3.2	5.3	5.7	5.0
7.1 - 8.0	3.9	2.6	4.8	3.1	3.6
8.1 - 9.0	4.3	2.0	3.7	3.9	3.5
9.1 - 10.0	2.2	2.2	2.8	2.5	2.4
10.1 - 11.0	1.6	1.6	2.0	2.2	1.9
11.1 +	12.5	7.7	15.1	12.8	12.0

Table 8.3

QUEBEC-LABRADOR REGION

Ventilation Coefficient ($m^2/sec \times 10^3$)	Percentage Frequencies (Mean)				
	Spring	Summer	Fall	Winter	Annual
0 - 1.0	5.5	4.3	12.5	35.4	14.4
1.1 - 2.0	9.5	5.6	12.8	18.8	11.7
2.1 - 3.0	9.5	4.6	11.9	12.2	9.6
3.1 - 4.0	7.8	7.2	10.7	9.8	8.9
4.1 - 5.0	8.1	7.2	8.5	6.8	7.7
5.1 - 6.0	10.8	5.6	6.9	5.9	7.3
6.1 - 7.0	9.4	5.7	5.9	3.2	6.1
7.1 - 8.0	6.5	4.9	4.6	1.6	4.4
8.1 - 9.0	6.3	5.2	4.2	2.0	4.4
9.1 - 10.0	5.7	5.8	3.8	1.5	4.2
10.1 - 11.0	3.5	3.3	2.1	.7	2.4
11.1 +	17.8	40.8	16.4	2.3	19.3

Table 9.3

MACKENZIE VALLEY REGION

Ventilation Coefficient ($m^2/sec \times 10^3$)	Percentage Frequencies (Mean)				
	Spring	Summer	Fall	Winter	Annual
0 - 1.0	21.3	6.4	46.5	79.8	38.5
1.1 - 2.0	18.3	8.9	14.9	11.3	13.4
2.1 - 3.0	12.1	8.8	10.9	4.8	9.2
3.1 - 4.0	8.9	8.9	6.7	1.7	6.6
4.1 - 5.0	7.8	9.1	5.6	1.2	5.9
5.1 - 6.0	6.6	9.1	3.3	.4	4.9
6.1 - 7.0	4.4	6.6	2.4	.1	3.4
7.1 - 8.0	3.1	6.2	2.2	.2	3.2
8.1 - 9.0	2.4	6.0	2.0	.2	2.7
9.1 - 10.0	2.4	5.6	1.1	.1	2.3
10.1 - 11.0	1.6	3.6	.8	0	1.5
11.1 +	11.3	20.9	3.9	.2	9.1

Table 10.3

HUDSON BAY REGION

Ventilation Coefficient ($m^2/sec \times 10^3$)	Percentage Frequencies (Mean)				
	Spring	Summer	Fall	Winter	Annual
0 - 1.0	21.5	10.7	24.8	54.7	27.9
1.1 - 2.0	21.0	10.7	17.0	20.2	17.2
2.1 - 3.0	14.8	10.5	13.2	10.6	12.3
3.1 - 4.0	10.3	9.7	10.0	5.0	8.8
4.1 - 5.0	6.6	8.6	6.9	3.4	6.4
5.1 - 6.0	3.3	8.7	5.9	2.0	5.0
6.1 - 7.0	4.6	6.0	4.4	1.1	4.0
7.1 - 8.0	3.7	5.4	3.5	1.0	3.4
8.1 - 9.0	2.9	4.6	2.7	.5	2.7
9.1 - 10.0	2.6	3.4	2.5	.5	2.3
10.1 - 11.0	1.9	3.5	1.8	.4	1.9
11.1 +	6.8	18.4	7.4	.9	8.4

Table 11.3

BAFFIN REGION

Ventilation Coefficient ($m^2/sec \times 10^3$)	Percentage Frequencies (Mean)				
	Spring	Summer	Fall	Winter	Annual
0 - 1.0	32.1	24.9	35.9	67.5	40.1
1.1 - 2.0	20.0	14.8	17.6	13.7	16.5
2.1 - 3.0	13.7	9.2	11.2	7.1	10.3
3.1 - 4.0	9.7	9.4	7.4	4.9	7.9
4.1 - 5.0	6.2	5.3	5.6	1.9	4.8
5.1 - 6.0	3.9	6.6	5.7	1.6	4.5
6.1 - 7.0	2.8	5.6	2.9	.6	3.0
7.1 - 8.0	2.8	3.0	3.2	.6	2.4
8.1 - 9.0	2.2	3.7	2.3	.5	2.2
9.1 - 10.0	2.2	3.0	2.0	.3	1.9
10.1 - 11.0	1.6	3.3	.9	.4	1.6
11.1 +	3.0	11.2	5.4	1.2	5.2

Table 12.3

HIGH ARCTIC REGION

Ventilation Coefficient ($m^2/sec \times 10^3$)	Percentage Frequencies (Mean)				
	Spring	Summer	Fall	Winter	Annual
0 - 1.0	57.8	36.6	61.3	79.9	58.9
1.1 - 2.0	17.7	22.3	16.4	11.0	16.9
2.1 - 3.0	10.5	15.1	8.0	5.6	9.8
3.1 - 4.0	5.1	8.7	4.3	2.1	5.1
4.1 - 5.0	3.0	5.6	3.8	1.0	3.4
5.1 - 6.0	2.4	3.8	1.9	.4	2.1
6.1 - 7.0	1.2	2.7	1.4	.2	1.3
7.1 - 8.0	.9	1.5	1.0	0	.9
8.1 - 9.0	.6	1.3	.7	0	.7
9.1 - 10.0	.3	.6	.4	0	.3
10.1 - 11.0	0	.3	.2	0	.1
11.1 +	.5	1.7	.6	0	.7

APPENDIX C

APPENDIX C

Part 1: Regional Summaries

Regional seasonal and annual % Frequencies (taken from the tables in Appendix B) are summarized for Significant Levels in the following categories:

1. Maximum (Afternoon) Mixing Heights:
   - i.) Less than 200 m
   - ii.) Less than 600 m
   - iii.) Greater than 2000 m
2. Mean Transport Wind Speeds:
   - i.) Less than 4.0 m/s
   - ii.) Greater than 12.0 m/s
3. Ventilation Coefficients:
   - i.) Less than 3000 m^2/s
   - ii.) Less than 6000 m^2/s

     (This is the U.S. standard lower limit or "threshold value" for low pollution potential in their air pollution forecast program).
   - iii.) Greater than 11000 m^2/s

Part 2: Regional Comparisons

The regions are ranked in order of decreasing % Frequencies in each of the categories identified in Part 1 above.

APPENDIX C - PART 1

REGIONAL SUMMARIES

APPENDIX C - PART 1:

SUMMARY - REGIONAL PERCENTAGE FREQUENCY AVERAGES

1. AFTERNOON MIXING LAYER HEIGHTS

	Spring	Summer	Fall	Winter	Annual
1. PACIFIC COAST					
200 m. -	4.1	3.4	22.1	18.6	12.1
600 m. -	25.2	39.6	76.4	80.5	55.4
2000 m. -	1.1	0	0	0	.3
2. ROCKIES					
200 m. -	2.9	1.2	11.5	35.9	12.9
600 m. -	13.5	5.5	45.9	86.7	37.9
2000 m. -	32.3	53.4	6.0	0	22.9
3. LEE OF THE ROCKIES					
200 m. -	5.2	1.9	9.8	37.2	12.4
600 m. -	23.6	7.6	35.2	85.3	35.8
2000 m. -	38.3	55.7	13.7	1.1	28.6
4. PRAIRIES					
200 m. -	5.4	1.7	8.4	23.8	9.4
600 m. -	31.7	14.7	40.6	91.6	43.2
2000 m. -	15.8	26.1	5.1	0	12.2
5. GREAT LAKES					
200 m. -	4.9	2.4	6.3	11.1	6.1
600 m. -	23.6	13.1	30.7	65.6	32.8
2000 m. -	13.8	15.3	2.4	0	8.1
6. APPALACHIANS					
200 m. -	2.8	1.1	4.5	8.7	4.3
600 m. -	18.6	9.4	27.9	53.9	27.5
2000 m. -	20.9	24.7	4.8	.5	12.7

	S	S	F	W	A
7. ATLANTIC COAST					
200 m. -	17.3	29.2	16.7	20.8	21.0
600 m. -	50.2	63.4	50.0	59.1	55.6
2000 m. -	1.7	1.6	.7	0	1.0
8. CENTRAL QUEBEC					
200 m. -	3.2	2.1	8.5	18.8	8.2
600 m. -	25.2	16.1	45.3	82.6	42.3
2000 m. -	5.5	23.2	3.0	0	7.9
9. MACKENZIE VALLEY					
200 m. -	9.7	2.5	28.9	59.3	25.1
600 m. -	42.4	16.4	67.4	97.9	56.1
2000 m. -	11.6	26.9	1.8	0	10.1
10. HUDSON BAY					
200 m. -	18.7	8.6	24.5	51.7	25.9
600 m. -	68.4	38.9	64.6	94.3	66.6
2000 m. -	2.1	6.3	.3	0	2.2
11. BAFFIN					
200 m. -	17.3	13.1	29.7	62.2	30.6
600 m. -	70.3	46.4	70.1	97.1	71.1
2000 m. -	.3	4.3	.3	0	1.2
12. HIGH ARCTIC					
200 m. -	55.2	30.6	60.7	83.8	57.6
600 m. -	93.2	80.1	93.5	99.6	91.6
2000 m. -	0	.3	0	0	0

APPENDIX C - PART I:

SUMMARY - REGIONAL PERCENTAGE FREQUENCY AVERAGES:

2. MEAN WIND SPEEDS THROUGH THE MIXING LAYER

	Spring	Summer	Fall	Winter	Annual
1. PACIFIC COAST					
4.0 m/s -	35.8	46.3	45.4	40.1	41.9
12.0 m/s -	5.2	.3	4.7	11.4	5.4
2. ROCKIES					
4.0 m/s -	30.2	37.2	37.2	53.2	39.5
12.0 m/s -	3.5	.9	4.4	3.7	3.2
3. LEE OF THE ROCKIES					
4.0 m/s -	21.7	21.5	20.5	47.6	27.8
12.0 m/s -	11.2	6.4	11.9	9.0	9.6
4. PRAIRIES					
4.0 m/s -	17.3	18.4	23.5	44.8	26.0
12.0 m/s -	10.1	6.9	9.7	4.1	7.7
5. GREAT LAKES					
4.0 m/s -	15.9	21.3	22.4	27.6	21.8
12.0 m/s -	11.1	5.5	8.9	7.0	8.1
6. APPALACHIANS					
4.0 m/s -	16.5	17.6	22.5	26.4	20.8
12.0 m/s -	13.5	6.7	10.2	10.9	10.3
7. ATLANTIC COAST					
4.0 m/s -	25.7	30.3	24.0	20.6	25.2
12.0 m/s -	12.7	5.6	12.3	21.8	13.3

	S	S	F	W	A
8. CENTRAL QUEBEC					
4.0 m/s -	22.2	21.5	23.9	40.0	26.9
12.0 m/s -	9.5	9.9	10.7	7.6	8.3
9. MACKENZIE VALLEY					
4.0 m/s -	47.1	38.0	58.3	77.7	55.3
12.0 m/s -	1.5	1.0	1.8	.8	1.3
10. HUDSON BAY					
4.0 m/s -	22.1	18.7	23.4	35.3	24.9
12.0 m/s -	11.2	9.8	14.4	9.3	11.2
11. BAFFIN					
4.0 m/s -	44.9	40.6	41.4	56.6	45.9
12.0 m/s -	6.5	4.4	7.3	7.6	6.5
12. HIGH ARCTIC					
4.0 m/s -	45.9	35.9	44.2	49.5	43.9
12.0 m/s -	7.4	4.4	8.0	4.9	6.2

SUMMARY - REGIONAL PERCENTAGE FREQUENCY AVERAGES:

3. VENTILATION COEFFICIENTS

	Spring	Summer	Fall	Winter	Annual
1. PACIFIC COAST					
3000 m^2/s -	35.6	53.7	72.8	66.5	57.2
6000 m^2/s -	65.3	83.3	91.3	87.5	81.9
11000 m^2/s -	9.7	2.3	1.1	1.2	3.6
2. ROCKIES					
3000 m^2/s -	17.5	9.5	46.2	80.4	38.5
6000 m^2/s -	37.7	26.1	68.1	92.9	56.3
11000 m^2/s -	35.2	39.9	13.3	2.2	22.7
3. LEE OF THE ROCKIES					
3000 m^2/s -	23.3	9.6	31.4	78.2	35.6
6000 m^2/s -	37.2	23.9	50.4	88.2	49.9
11000 m^2/s -	45.1	55.4	30.0	5.4	34.0
4. PRAIRIES					
3000 m^2/s -	25.3	14.2	37.0	80.2	39.3
6000 m^2/s -	49.7	35.4	62.8	96.5	61.3
11000 m^2/s -	30.0	37.2	17.9	.4	21.4
5. GREAT LAKES					
3000 m^2/s -	20.5	15.6	28.8	55.9	30.3
6000 m^2/s -	42.9	39.0	55.0	82.7	55.1
11000 m^2/s -	29.3	31.2	19.4	5.0	21.2

	S	S	F	W	
6. APPALACHIANS					
3000 m^2/s -	15.2	9.5	25.0	46.3	24.0
6000 m^2/s -	32.6	27.8	48.0	71.6	45.0
11000 m^2/s -	40.4	42.3	24.7	10.8	29.6
7. ATLANTIC COAST					
3000 m^2/s -	44.0	61.3	44.5	48.0	49.5
6000 m^2/s -	69.8	81.0	66.4	70.1	72.0
11000 m^2/s -	12.5	7.7	15.1	12.8	12.0
8. CENTRAL QUEBEC					
3000 m^2/s -	24.5	14.5	37.2	66.4	35.7
6000 m^2/s -	51.2	34.5	63.3	88.9	59.6
11000 m^2/s -	17.8	40.8	16.4	2.3	19.3
9. MACKENZIE VALLEY					
3000 m^2/s -	51.7	24.1	72.3	95.9	61.1
6000 m^2/s -	75.0	51.2	87.9	99.2	78.5
11000 m^2/s -	11.3	20.9	3.9	.2	9.1
10. HUDSON BAY					
3000 m^2/s -	57.3	31.9	55.0	85.5	57.4
6000 m^2/s -	77.5	58.9	77.8	95.9	77.6
11000 m^2/s -	6.8	18.4	7.4	.9	8.4
11. BAFFIN					
3000 m^2/s -	65.8	48.9	64.7	88.3	66.9
6000 m^2/s -	85.6	70.2	83.4	96.7	84.1
11000 m^2/s -	3.0	11.2	5.4	1.2	5.2
12. HIGH ARCTIC					
3000 m^2/s -	86.0	74.0	85.7	96.5	85.6
6000 m^2/s -	96.5	92.1	95.7	100.0	96.2
11000 m^2/s -	.5	1.7	.0	0	.2

APPENDIX C - PART 2

REGIONAL COMPARISONS

APPENDIX C Part 2: Regional Comparisons

Tables 1-4: Regional Percentage Frequency of Occurrence of Maximum Afternoon Mixing Heights Less Than 200 m. (Ranked in order of decreasing frequencies)

Table 1. Spring

1.	High Arctic	55.2%
2.	Hudson Bay	18.7
3.	Baffin	17.3
4.	Atlantic	17.3
5.	Mackenzie Valley	9.7
6.	Prairies	5.4
7.	Lee Rockies	5.2
8.	Great Lakes	4.9
9.	Pacific	4.1
10.	Central Quebec	3.2
11.	Rockies	2.9
12.	Appalachians	2.8

Table 2. Summer

1.	High Arctic	30.6%
2.	Atlantic	29.2
3.	Baffin	13.1
4.	Hudson Bay	8.6
5.	Pacific	3.4
6.	Mackenzie Valley	2.5
7.	Great Lakes	2.4
8.	Quebec	2.1
9.	Lee Rockies	1.9
10.	Prairies	1.7
11.	Rockies	1.2
12.	Appalachians	1.1

Table 3. Fall

1.	High Arctic	60.7%
2.	Baffin	28.9
3.	Mackenzie Valley	28.9
4.	Hudson Bay	24.5
5.	Pacific	22.1
6.	Atlantic	16.7
7.	Rockies	11.5
8.	Lee Rockies	9.8
9.	Quebec	8.5
10.	Prairies	8.4
11.	Great Lakes	6.3
12.	Appalachians	4.5

Table 4. Winter

1.	High Arctic	83.8%
2.	Baffin	62.2
3.	Mackenzie Valley	59.3
4.	Hudson Bay	51.7
5.	Lee Rockies	37.2
6.	Rockies	35.9
7.	Prairies	23.8
8.	Atlantic	20.8
9.	Quebec	18.8
10.	Pacific	18.6
11.	Great Lakes	11.1
12.	Appalachians	8.7

Tables 5-8: Regional Percentage Frequency of Occurrence of Maximum Afternoon Mixing Heights Less Than 600 m. (Ranked in order of decreasing frequencies)

Table 5. Spring			Table 6. Summer	
1.	High Arctic	93.2%	1. High Arctic	80.1%
2.	Baffin	70.3	2. Atlantic	63.4
3.	Hudson Bay	68.4	3. Baffin	46.4
4.	Atlantic	50.2	4. Pacific	39.6
5.	Mackenzie V.	42.4	5. Hudson Bay	38.9
6.	Prairies	31.7	6. Mackenzie V.	16.4
7.	Quebec	25.2	7. Quebec	16.1
8.	Pacific	25.2	8. Prairies	14.7
9.	Lee Rockies	23.6	9. Great Lakes	13.1
10.	Great Lakes	23.6	10. Appalachians	9.4
11.	Appalachians	18.6	11. Lee Rockies	7.6
12.	Rockies	13.5	12. Rockies	5.5

Table 7. Fall			Table 8. Winter	
1.	High Arctic	93.5%	1. High Arctic	99.6%
2.	Pacific	76.4	2. Mackenzie V.	97.9
3.	Baffin	70.1	3. Baffin	97.1
4.	Mackenzie V.	67.4	4. Hudson Bay	94.3
5.	Hudson Bay	64.6	5. Prairies	91.6
6.	Atlantic	50.0	6. Rockies	86.7
7.	Rockies	45.9	7. Lee Rockies	85.3
8.	Quebec	45.3	8. Quebec	82.6
9.	Prairies	40.6	9. Pacific	80.5
10.	Lee Rockies	35.2	10. Great Lakes	65.6
11.	Great Lakes	30.7	11. Atlantic	59.1
12.	Appalachians	27.9	12. Appalachians	53.9

Tables 9-12: Regional Percentage Frequency of Occurrence of Maximum Afternoon Mixing Heights Greater Than 2000 m. (Ranked in order of decreasing frequencies)

Table 9. Spring

1.	Lee Rockies	38.3%
2.	Rockies	32.3
3.	Appalachians	20.9
4.	Prairies	15.8
5.	Great Lakes	13.8
6.	Mackenzie V.	11.6
7.	Quebec	5.5
8.	Hudson Bay	2.1
9.	Atlantic	1.7
10.	Pacific	1.6
11.	Baffin	1.1
12.	High Arctic	0

Table 10. Summer

1.	Lee Rockies	55.7%
2.	Rockies	53.4
3.	Mackenzie V.	26.9
4.	Prairies	26.1
5.	Appalachians	23.2
6.	Quebec	20.2
7.	Great Lakes	15.3
8.	Hudson Bay	6.3
9.	Baffin	5.3
10.	Atlantic	1.6
11.	High Arctic	.3
12.	Pacific	0

Table 11. Fall

1.	Lee Rockies	13.8%
2.	Rockies	6.1
3.	Prairies	5.1
4.	Appalachians	4.8
5.	Quebec	2.7
6.	Great Lakes	2.4
7.	Mackenzie V.	1.8
8.	Atlantic	.7
9.	Baffin	.3
10.	Hudson Bay	.3
11.	Pacific	0
12.	High Arctic	0

Table 12. Winter

1.	Lee Rockies	1.1%
2.	Appalachians	.5
	Rest	0

Tables 13-16: Regional Percentage Frequency of Occurrence of Mean Transport Wind Speeds Through the Mixed Layer Less Than 4.0 m/s. (Decreasing frequencies)

Table 13. Spring

1.	Mackenzie Valley	47.1%
2.	High Arctic	45.9
3.	Baffin	44.9
4.	Pacific	35.8
5.	Rockies	30.2
6.	Atlantic	25.7
7.	Quebec	22.2
8.	Hudson Bay	22.1
9.	Lee Rockies	21.7
10.	Prairies	17.5
11.	Appalachians	16.5
12.	Great Lakes	15.9

Table 14. Summer

1.	Pacific	46.3%
2.	Baffin	40.6
3.	Mackenzie V.	38.0
4.	Rockies	37.2
5.	High Arctic	35.9
6.	Atlantic	30.3
7.	Quebec	21.5
8.	Lee Rockies	21.5
9.	Great Lakes	21.3
10.	Hudson Bay	18.7
11.	Prairies	18.4
12.	Appalachians	17.6

Table 15. Fall

1.	Mackenzie V.	58.3%
2.	Pacific	45.4
3.	High Arctic	44.2
4.	Baffin	41.4
5.	Rockies	37.2
6.	Atlantic	24.0
7.	Quebec	23.9
8.	Prairies	23.5
9.	Hudson Bay	23.4
10.	Appalachians	22.5
11.	Great Lakes	22.4
12.	Lee Rockies	20.4

Table 16. Winter

1.	Mackenzie V.	77.7%
2.	Baffin	56.6
3.	Rockies	53.2
4.	High Arctic	49.5
5.	Lee Rockies	47.6
6.	Prairies	44.8
7.	Pacific	40.1
8.	Quebec	40.0
9.	Hudson Bay	35.3
10.	Great Lakes	27.6
11.	Appalachians	26.4
12.	Atlantic	20.6

Tables 17-20: Regional Percentage Frequency of Occurrence of Mean Transport Wind Speeds Through the Mixed Layer Greater Than 12.0 m/s. (Decreasing frequencies)

Table 17. Spring

1.	Appalachian	13.5%
2.	Atlantic	12.7
3.	Hudson Bay	11.2
4.	Lee Rockies	11.2
5.	Great Lakes	11.1
6.	Prairies	10.1
7.	Quebec	9.5
8.	High Arctic	7.4
9.	Baffin	6.5
10.	Pacific	5.2
11.	Rockies	3.5
12.	Mackenzie V.	1.5

Table 18. Summer

1.	Quebec	9.9%
2.	Hudson Bay	9.8
3.	Prairies	6.9
4.	Appalachians	6.7
5.	Lee Rockies	6.4
6.	Atlantic	5.6
7.	Great Lakes	5.5
8.	Baffin	4.4
9.	High Arctic	4.4
10.	Mackenzie V.	1.0
11.	Rockies	.9
12.	Pacific	.3

Table 19. Fall

1.	Hudson Bay	14.4%
2.	Atlantic	12.3
3.	Lee Rockies	11.9
4.	Quebec	10.7
5.	Appalachians	10.2
6.	Prairies	9.7
7.	Great Lakes	8.9
8.	High Arctic	8.0
9.	Baffin	7.3
10.	Pacific	4.7
11.	Rockies	4.4
12.	Mackenzie V.	1.8

Table 20. Winter

1.	Atlantic	21.8%
2.	Pacific	11.4
3.	Appalachians	10.9
4.	Hudson Bay	9.3
5.	Lee Rockies	9.0
6.	Baffin	7.6
7.	Quebec	7.6
8.	Great Lakes	7.0
9.	High Arctic	4.9
10.	Prairies	4.1
11.	Rockies	3.7
12.	Mackenzie V.	.8

Tables 21-24: Regional Percentage Frequency of Occurrence of Maximum Afternoon Ventilation Coefficients Less Than 6000 m^2/s. (Decreasing frequencies).

Table 21. Spring

1.	High Arctic	96.5%
2.	Baffin	85.5
3.	Hudson Bay	77.5
4.	Mackenzie V.	75.0
5.	Atlantic	69.8
6.	Pacific	65.3
7.	Quebec	51.2
8.	Prairies	49.7
9.	Great Lakes	42.9
10.	Rockies	37.7
11.	Lee Rockies	37.2
12.	Appalachians	32.6

Table 22. Summer

1.	High Arctic	92.1%
2.	Pacific	83.3
3.	Atlantic	81.0
4.	Baffin	70.2
5.	Hudson Bay	58.9
6.	Mackenzie V.	51.2
7.	Great Lakes	39.0
8.	Prairies	35.4
9.	Quebec	34.5
10.	Appalachians	27.8
11.	Rockies	26.1
12.	Lee Rockies	23.9

Table 23. Fall

1.	High Arctic	95.7%
2.	Pacific	91.3
3.	Mackenzie V.	87.9
4.	Baffin	83.4
5.	Hudson Bay	77.8
6.	Rockies	68.1
7.	Atlantic	66.4
8.	Quebec	63.3
9.	Prairies	62.8
10.	Great Lakes	55.0
11.	Lee Rockies	50.4
12.	Appalachians	48.1

Table 24. Winter

1.	High Arctic	100.0%
2.	Mackenzie V.	99.2
3.	Baffin	96.7
4.	Prairies	96.5
5.	Hudson Bay	95.9
6.	Rockies	92.9
7.	Quebec	88.9
8.	Lee Rockies	88.2
9.	Pacific	87.5
10.	Great Lakes	82.7
11.	Appalachians	71.6
12.	Atlantic	70.1

Tables 25 - 28: Regional Percentage Frequencies of Occurrence of Maximum Afternoon Ventilation Coefficients Less Than 3000 m^2/s (decreasing frequencies).

Table 25. Spring

1.	High Arctic	86.0 %
2.	Baffin	65.8
3.	Hudson Bay	57.3
4.	Mackenzie V.	51.7
5.	Atlantic	44.0
6.	Pacific	35.6
7.	Prairies	25.3
8.	Quebec	24.5
9.	Lee Rockies	23.3
10.	Great Lakes	20.5
11.	Rockies	17.5
12.	Appalachians	15.2

Table 26. Summer

1.	High Arctic	74.0 %
2.	Atlantic	61.3
3.	Pacific	53.7
4.	Baffin	48.9
5.	Hudson Bay	31.9
6.	Mackenzie V.	24.1
7.	Great Lakes	15.6
8.	Quebec	14.5
9.	Prairies	14.2
10.	Lee Rockies	9.6
11.	Rockies	9.5
12.	Appalachians	9.5

Table 27. Fall

1.	High Arctic	85.7 %
2.	Pacific	72.8
3.	Mackenzie V.	72.3
4.	Baffin	64.7
5.	Hudson Bay	55.0
6.	Rockies	46.2
7.	Atlantic	44.5
8.	Quebec	37.2
9.	Prairies	37.0
10.	Lee Rockies	31.4
11.	Great Lakes	28.8
12.	Appalachians	25.0

Table 28. Winter

1.	High Arctic	96.5 %
2.	Mackenzie V.	95.9
3.	Baffin	88.3
4.	Hudson Bay	85.5
5.	Rockies	80.4
6.	Prairies	80.2
7.	Lee Rockies	78.2
8.	Pacific	66.5
9.	Quebec	66.4
10.	Great Lakes	55.9
11.	Atlantic	48.0
12.	Appalachians	46.3

Tables 29 - 32: Regional Percentage Frequencies of Occurrence of Maximum Afternoon Ventilation Coefficients Greater Than 11,000 m^2/s (decreasing frequencies).

Table 29. Spring

1.	Lee Rockies	45.1 %
2.	Appalachians	40.4
3.	Rockies	35.2
4.	Prairies	30.0
5.	Great Lakes	29.3
6.	Quebec	17.8
7.	Atlantic	12.5
8.	Mackenzie V.	11.3
9.	Pacific	9.7
10.	Hudson Bay	6.8
11.	Baffin	3.1
12.	High Arctic	.5

Table 30. Summer

1.	Lee Rockies	55.4 %
2.	Appalachians	42.3
3.	Quebec	40.8
4.	Rockies	39.9
5.	Prairies	37.2
6.	Great Lakes	31.2
7.	Mackenzie V.	20.9
8.	Hudson Bay	18.4
9.	Baffin	11.2
10.	Atlantic	7.7
11.	Pacific	2.3
12.	High Arctic	1.7

Table 31. Fall

1.	Lee Rockies	30.0 %
2.	Appalachians	24.7
3.	Great Lakes	19.4
4.	Prairies	17.9
5.	Quebec	16.4
6.	Atlantic	15.1
7.	Rockies	13.3
8.	Hudson Bay	7.4
9.	Baffin	5.4
10.	Mackenzie V.	3.9
11.	Pacific	1.1
12.	High Arctic	.6

Table 32. Winter

1.	Atlantic	12.8 %
2.	Appalachians	10.8
3.	Lee Rockies	5.4
4.	Great Lakes	5.0
5.	Quebec	2.3
6.	Rockies	2.2
7.	Baffin	1.4
8.	Pacific	1.2
9.	Hudson Bay	.9
10.	Prairies	.4
11.	Mackenzie Valley	.2
12.	High Arctic	0

APPENDIX D

APPENDIX D: Rawinsonde Station Site Documentation

Introduction

The mesoscale conditions surrounding the radiosonde release area have significant effect on the data, especially in the lowest 1000 metres above the surface. For this reason, in the assessment of upper-air statistics, an awareness of nearby topography is essential.

Method

The rawinsonde system of measurement of the upper atmosphere consists of a balloon-borne radiosonde, a receiving-tracking unit and a recorder. Information is transmitted from the radiosonde by radiosignal as it is tracked in flight (using the principal of radio-direction finding). By using this Ground Monitoring Device (GMD), the vertical profile of barometric pressure, temperature and relative humidity are measured during a single sounding up to 30 KM altitude. The wind speed and direction are obtained from theodolite bearings. (The elevation angle is used to obtain the horizontal distance of the balloon from the station).

Radiosonde flights are conducted twice daily at 0000 GMT and 1200 GMT, at all radiosonde stations in an international network. The primary purpose is to provide information for upper-air charts used operationally in weather forecasting.

In reporting sounding data, significant levels are specified if the temperature deviates by one degree Celcius or more from a straight line through temperature points at adjacent mandatory levels. (i.e. By definition, significant levels must produce the temperature profile to within 1°C of the actual observed value.)

Temperature measurements lose accuracy due to a sensor lag. Only 63% of the instantaneous temperature change in no more than 30 metres is detected. This limitation inherent in rawinsonde instrumentation response requires that all data recorded within 10 mb. of the surface (approximately the lowest 80 metres) must not be evaluated because of its unreliability.

Unfortunately, this is a critical layer in air pollution studies, since pollution sources and impact receptors are confined in the lowest 100 metres immediately above the surface. In addition, difficult to measure terrain-dependent meso- and microscale interactions dominate at this level.

Another major problem in the measurement of the boundary layer using rawinsonde equipment is low elevation angles. These cases are normally associated with strong wind shear at lower levels. Problems arise due to the limiting-angle zone around the station site regarded as extending 6 degrees in elevation above the horizon or any object on the horizon (with the exception of trees).

The accuracy of the GMD (Ground Measuring Device) tracking system is seriously effected whenever angular readings fall within this zone. The boundaries of the zone are a function of the individual installation. (Note: Certain stations use the Transpondersonde Ranging System (TSRS) which uses slant range instead of elevation angle. This is the distance between the receiver and balloon, and it gives more accurate winds especially at low elevation angles.)

Summary

In summary, a number of the limitations in using rawinsonde data to measure conditions in the lowest layer of the atmosphere include the following:

1. Limited spatial resolution. The rawinsonde network is designed to optimize the synoptic-scale influences above the boundary layer.

2. Although the existing standard WMO meteorological network is designed to minimize the influence of local surface conditions, in the lowest 1000 metres local mesoscale effects camouflage regional synoptic-scale phenomena and make extrapolation of the radiosonde data to even a nearby site risky.

3. The soundings are not truly vertical depending on wind shear and resultant angular measurement.

4. Instrument response through the lowest 100 metres where the balloon rises rapidly and where eddies and fluxes are most extreme through small horizontal and vertical distances, make this data unreliable.

5. Transmission errors.

In using the data, one clearly recognizes the shortcomings of the rawinsonde system (both spatially and technically), particularily in air pollution potential studies involving the lowest 2000 metres above the surface.

However, it is the only consistently reporting upper air system across the country with any period of operation.

Station Descriptions

The following descriptions of the rawinsonde sites are divided according to the regional divisions identified in this study.

Region 1: Pacific

In the data set examined, a single radiosonde station is available that is located in the Pacific coast area. In the proposed 10-15 year data set, Annette, Yakutak and Quillayute will be included in addition to Port Hardy.

Port Hardy (17 M) -

This station is located on the northern tip of Vancouver Island, near the shores of Queen Charlotte Strait. The mainland is about 30 KM to the east. There are heavily forested hills and mountains throughout the area. The highest elevations are to the east on the mainland. To the south, they range between 1000 M to 1500 M while in the west they are only around 800 M.

The area around the site is swampy in part, and hilly and densley wooded to the west. In the immediate vicinity of the release area, there is extensive asphalt cover.

Pacific Ocean

This is the largest ocean in the world, covering an area greater than the combined area of all the continents. The average depth is 3.5 KM (2.2 miles) but the deepest point (Challenger Deep) is 11 KM (almost 7 miles) deep.

Region 2: Rockies

All three stations in this region are located in a valley (plateau) relative to the surrounding mountains (i.e. at 700 M which is 1000 to 3000 M below the surrounding slopes). Vernon is not included since it was not in operation until 1970. However, it will be included in the next data set.

Whitehorse (699.5 M) - is situated on a broad plateau about 1 KM west of the Yukon River. The river valley runs 60 to 80 M below the plateau with steep escarpments along the banks. The Pacific Ocean is 250 KM to the west, but only about 1000 KM south is a canal that extends inland from the ocean. However, a large intervening barrier 2500 to 3000 M extends along the coast, which rise even higher to the west (St. Elias Mountains, 4000 to 6000 M). Nearby tops reach only 1500 to 2000 M.

The 25 KM wide valley floors parallel to the mountain ridges are heavily wooded. Deep lakes in the area include Bennett Lake 85 KM to the south, Lake Laberge 30 KM to the north, and Schwatka Lake about 1 KM to the southeast.

Prince George (691.3 M) - is on a flat plateau 90 M above the Fraser River along a north-south oriented valley. Gently rolling farmland to the east have large open areas of hay fields. To the west, the slopes are heavily wooded. The Tabor Mountain Range (1000 to 1200 M) projects above the horizon in the eastern sector. Tabor Lake covers 600 acres at the base of this range. In the south, George Mountains have tops to 1800 M.

There is a large forestry industry, chemical plants and a refinery in the area.

Spokane (721 M) - not available.

Region 3: Lee of the Rockies

Edmonton - Stony Plain (766 M) - is located on a slightly rolling plain that slopes eastward at a rate of about 2 M /KM. No area within 3 KM of the station exceeds the height of the site. Many small lakes and rivers dot the countryside. Lake Wabaumun is 25 KM west and Lac St. Ann is 25 KM to the northwest. The North Saskatchewan River passes 20 KM to the south. There are a few treed areas but it is mainly cleared and open for grazing and ranching or grain farming. Edmonton is 45 KM east with heavy industry and oil refineries.

Great Falls (1180 M) - not available.

Glasgow (636 M) - not available.

Region 4: Prairies

The Pas (273 M) - The countryside surrounding the station is generally flat. No area in 3 KM varies more than within 15 M of the station elevation. There is extensive coniferous forest in the area. There are numerous large and small lakes, the largest of which is Clearwater Lake to the northeast. A great deal of the area is muskeg and marshland with sandy clay and gravel in a few places.

Bismarck (506 M) - not available.

Region 5: Great Lakes

Sault Ste. Marie (220 M) -
International Falls (360 M) -
Green Bay (214 M) -
Flint (238 M) -
Buffalo (217 M) -

These are all northern U.S. border radiosonde stations, and site documentation is not available.

General - 60% of the land area around the Great Lakes is below 30 M.

Lake Superior - is the world's largest fresh water lake covering an area of 82,400 square kilometres (i.e. over 30,000 square miles).

Maniwaki (170 M) - lies along the Gatineau River Valley that runs north-south. Very dense fog forms almost nightly. Hills surrounding the site have an average elevation of 250 KM to 300 KM. There is extensive forest in the area, and the principle industry is timber.

Region 6: Appalachians

This region is probably representative of only a small portion of extreme northwestern New Brunswick. It is an extension of the U.S. Appalachian Region which displays relatively higher mean mixing heights than their maritime counterparts to the east (the Atlantic) and to the west (the Great Lakes). It is included for completeness and continuity.

The two stations included in the region are: Albany (84 M) and Caribou (189 M) - both unavailable.

Region 7: Atlantic

Argentia (15.5 M) - is on a flat gravelled plateau surrounded by water except for the isthmus to the south. 60 M to the west, the land drops abruptly to the shoreline of Placentia Bay. To the east, there is a gradual downslope to Argentia harbour. On the east side of the harbour, (3 KM from the station) the land rises rapidly to elevations of 150 M.

Stephenville (26.2 M) - A large grassed area is surrounded by almost continuous flat terrain. St. George's Bay is immediately southwest. Hills 150 to 200 M high surround the site from the northwest around to the east, 5 to 10 KM away. The highest peak is to the north (elevation 550 M).

Sept Isles (54.9 M) - The release area is a grass field surrounded by pine trees. The land slopes gently to the St. Lawrence River. Snow is piled high all around the area in the winter.

Sable Island (3 M) - is a small island completely surrounded by the coastal waters of the Atlantic Ocean. It is a slightly rolling, treeless island of only scrub grass vegetation. The Labrador Current passes nearby.

Region 8: Central Quebec

For convenience, this region is described as central Quebec, although it encompasses a large section of Labrador.

Nitchequon (536.1 M) - is located on a ridge of land on the south end of Nitchequon Island on the northern tip of Nitchequon Lake which covers 2000 square KM. A ridge (700 M) encircles the northern quadrant at a distance of 15-20 KM. The island is mainly forested.

Goose (46 M) - is on an elevated plateau between Hamilton Inlet and Goose River. The former stretches 200 KM inland from the Atlantic. The highest elevations on either side of the narrows are about 350 M and climb to about 600 M to the northwest. Nearby to the west, elevation rises abruptly to 300 M and is deeply cut by the Hamilton River Valley.

Black spruce covers much of the area, with extensive moss and marsh along the river. Forest fires are a problem in the summer due to the intense heating of the elevated plateau.

Region 9: Mackenzie Valley

Inuvik (68.0 M) - is on the east side of the East Channel of the Mackenzie River Delta, almost 100 KM south of the Beaufort Sea. The delta (12th largest in the world and about 160 KM across) is confined between mountains on the west and hills and rolling plains to the east. The Richardson Mountains (1140 M) are 80 KM to the west. Running parallel to the East Channel for about 50 KM is the Caribou Hills (180 M) about 40 KM north-northwest of the station. The largest lake in the area is 25 KM northeast. Over 40 KM to the north-northeast is a vast series of interconnected lakes to the Arctic coast (Eskimo Lakes).

The surrounding area lies on the northern edge of the tree line and has a combined Arctic and sub-Arctic environment. The countryside is mainly muskeg with numerous potholes and sparsely treed plateaus.

Norman Wells (73.2 M) - is on the north side of the Mackenzie River (3.2 KM wide), 180 M from the shore. To the north runs the Norman Range (with peaks to 900 M) which drops sharply to a deep valley and sheltered lake 600 M below. To the east are airport buildings and hills. To the south, the flat land tapers to the river. About 65 KM beyond in the same direction,

the major mountain range (Mackenzie Mountains) climbs to 2400 M Dense forestation extends to the west. Within a 3 KM radius of the station, dense bush and a closed forest with tops to 10 M reach on all sides. The sub-soil base is slate and clay, with a rich organic humus layer on top. An oil refinery is situated 1.5 KM to the west.

Fort Smith (204.2 M) - is 60 M southwest of the south bank of the Slave River. (The width of the river varies from 1 to 3 KM across). The river is about 40 M below the station level, and about 20 KM to the east, four sets of rapids give another drop of about 30 M.

The area is mostly flat. There is rapid growth of vegetation in the long daylight hours during the short summer. The immediate area is surrounded on all quadrants (except the north-northeast) by heavy stands of timber 10 to 15 M high. There is also extensive marshland.

The northern boundary of Wood Buffalo National Park is 1.5 KM to the south.

Fort Nelson (381.9 M) - is in a valley location with the Fort Nelson River running 3 KM to the east, and the Muskawa River to the south. Within a 15 KM radius, the highest elevation is 660 M. The land rises rapidly towards the town about 10 KM to the west. In the east and southeast, there are two hills greater than 450 M.

The surrounding country is densley wooded with some tops exceeding 22 M. The ground is clay with a thin layer of loam and organic soil. There is an active lumber industry in the area.

Region 10: Hudson Bay

Coral Harbour (62 M) - is located about 8 KM north of an inlet (South Bay) which opens onto the Hudson Bay. The terrain rises steadily from 60 M at the site to near 600 M at Porslid Mountain 65 KM to the north. Gently rolling glacial plains of mainly rock, shale and tundra extend on all sides to the waters of Hudson Bay. There are many small lakes and rivers on the island, (Southampton Island). The site has good exposure in all directions.

Baker Lake (9 M) - is situated at the extreme west end of a 70 KM long and 35 KM wide lake. The lake has numerous islands scattered throughout. Blueberry Hill (130 M) is about 3 KM to the south-west. Northeast of the station (about 1 KM), rock outcrops extend for 1 KM in an east-west orientation. There are no trees except for willows in sheltered places around the water.

Churchill (29 M) - is located about 1 KM south of the shore of Hudson Bay. The topography is very flat. The highest point within 30 KM is a rocky outcrop (50 M) 13 KM to the west-southwest. Due to the tides, there are open leads at the mouth of the Churchill River to the west, and on the Hudson Bay from time to time during the winter. A local steam plant injects moisture into the air.

Trout Lake (219.5 M) - is on the eastern extremity of Post Island completely surrounded by water in the Big Trout Lake. The shore is 100 M to the south. The site is on the gently

rolling landscape of the Canadian Shield (primarily granite and rock) and surrounded by dense bush and extensive muskeg. The release area is poor with a limiting angle of greater than 13 degrees to the west-northwest.

Moosonee (10.4 M) - is on the west bank of the Moose River north of the village and southwest of James Bay. It is bounded by flat, wooded terrain to the south, west and north. To the east, all bush is removed to the river. Some trees have tops to 10 M. Moose Factory is directly across the river.

Inoudjouac (7 M) - is situated on a sand penninsula on the southwest bank of the mouth of the Innuksuak River and just north of the Hudson Bay. North of the station the mainland is hilly (90 to 120 M). The highest point in 15 KM is 160 M. The immediate surrounding is only sand but further inland becomes muskeg and tundra.

Region 11: Baffin

Fort Chimo (37.2 M) - is on a hill on the north shore of the Kaksook River with Ungava Bay almost 60 KM to the north. Over 6 M tides move up the river periodically. The land in the northern quadrant is hilly, and blocks 1/10 of the sky to the north and east. The highest point in 15 KM is to the northeast (200 M).

The land on all sides is forested and rocky with numerous bogs and marshes and lakes, The tree limit is 35 KM to the north, and the tundra begins.

Clyde (25.3 M) - lies between the Baffin Bay and a line of hills that rise 5 degrees between the northeast and southeast quadrants. The highest (Black Bluff) rises 6.8 degrees to the southeast and is 500 M.

Frobisher Bay (33.5 M) -

From the south to the northwest, the land is hilly. The inlet lies to the southeast. From the northwest to the southeast orientation, the land is relatively flat and channels the wind along the bay. (85% of the winds are from the northwest or the southeast). There is only sparse tundra vegetation in the area.

The highest tides in the world occur at Frobisher Bay. (At low tide, numerous small islands appear in the Koojese Inlet). The area is almost completely ice and snow covered for about 7 months of the year.
(Two miles northeast of the station, a flow of hot water is drained regularily from the power plant).

Region 12: High Arctic

During the period of data used in this study (1965 to 1969), Cambridge Bay is not yet a functioning upper-air station. Coppermine, farther west, is the alternate site in operation at the time. Thus, the radiosonde network across the northern islands has a large unmonitored area from Victoria Island to northwestern Baffin Island.

The data sparsity leaves considerable room for subjectivity in preparing the frequency pattern. In spite of this areal limitation, the number of representative stations over the High Arctic region is greater than that of other regions in Canada.

The stations used in the regional frequency calculations are the following:

1. Alert: (el. 66.1 m) is located on the northeastern tip of Ellesmere Island, 1.5 km from a bay which opens onto the predominantly ice-covered Lincoln Sea and Arctic Ocean.

This is the most northern station in Canada, only 725 km from the North Pole. The nearby terrain is a gently rolling clay and shale surface, void of vegetation. There is higher relief 8 km to the south (450 to 600 m in height). 50 km to the southwest, snow capped peaks extend to 2900 m , (United States Range). The rugged Greenland coast lies 65 km to the east, across the narrow Robinson Channel.

2. Eureka: (el. 10.5 m) is on the north shore of Slidre Fiord on Ellesmere Island. Mountains in the order of 1800 to 2500 m enclose three sides of the station providing a natural barrier against the fierce Arctic winds. Strong and gusty winds do funnel along the river valley that meanders inland on a northward course.

The soil composition is a silty gravel with an abundance of dwarfed vegetation in the short summer. This type of soil with its permafrost base is very hard and dry in the winter and very soft and wet in the summer.

3. Isachsen:(el. 25.? m) is on the western shore of Elief Ringnes Island that borders the Arctic Ocean. It is located in a hollow between three sharp 150 to 250 m ridges from the west to the northeast, and bordered by Louise Bay 40 m to the southeast. All of the surrounding water bodies are frozen most of the year, except for a shore lead about 5 to 10 m wide in the bay.

The terrain is a contrast of sharp slopes of shale and erosions cut in numerous small ridges. Vegetation is limited to moss and lichen less than 12.5 cm.

Anabatic winds carry fog inland from the bay and katabatic winds move down the cove.

4. Mould Bay: (el. 15.0 m) is also on an island (Prince Patrick) bordering the Arctic Ocean. The station is located, however, on the east side about half way up a 40 km long bay. Prominent cliffs are evident on the west side of the bay about 6.5 km southwest of the station. The island is part of the lowland of the Arctic coastal plain, with an average level of about 150 m. The maximum elevation (275 m) is 20 km to the southwest.

Crozier Channel and McClure Strait to the east and southeast, respectively, remain ice-filled in the summer. Mould Bay is solid packed ice from October to May. The terrain is snow-free in July and August except for deep snow banks in ravines and hollows. The surface is mainly bedrock but, the sandy loam has an active layer in which marsh vegetation develops in late August.

5. Resolute Bay: (el. 40.0 m) is on a peninsula on Cornwalis Island with the sea 2.5 to 5.0 km on three sides. The station is on a plain sloping gently to the sea to the south. The upland plateau (180 to 250 m) extends 1 km to the northeast. There is a large, rounded promitory (Cape Martyr, 180 m) about 5 km to the southwest.

The soil is mainly crushed shale with plant cover less than 5% and 10 cm during the growing season. A lush, brown moss surrounds a dozen or so lakes that dot the area within 15 km to the northwest. The sea to the south (Barrow Strait) is frozen from mid-October to early July. Drift ice moves in and out of the bay all summer.

6. Sachs Harbour: (el. 85.6 m) is on a ridge overlooking the Beaufort Sea about 1 km to the south. To the east, north and west, a slightly rolling expansive plain extends to a chain of hills (45.0 to 60.0 m) in an east-west line 20 km to the north of the station. At the base of the hills, a river drains the whole plain. The terrain is generally rock and gravel with a few loam and silt deposits. Just east of the station, there is a great deposit of sand. The vegetation is mainly tundra and stunted trees (crawling vines). In the winter, there is not a great deal of snow accumulation due to the exposure.

7. Coppermine: (el. 22.3 m) is about 1 km south of the coast of the Coronation Gulf and 1.5 km southwest of the community. The surrounding country is generally flat muskeg with occasional low rocky outcroppings. There are a few rocky hills to the south and southwest about 45 m above the station.

8. Hall Beach: (el. 7.9 m) is on the well-exposed eastern shore of Melville Peninsula about .5 km to the west of the waters of Foxe Basin (visible from the station). The terrain slopes gently to 30 m about 6.5 km west of the station. The highest point in 35 km is less than 60 m.

The ground is made up of a flat, glaciated gravel base interspersed with patches of moss, grasses and stunted vegetation. The land is one-third covered with shallow pools of water in the summer. Foxe Basin is completely frozen from fall to spring, with an almost permanent lead about 10 to 15 km offshore.

APPENDIX E

APPENDIX E - Special Cases: Allowances for C-, U- and M-type Cases.

Tabulations of the mixing depth parameter are given separately for 'unlimited' mixing cases (U). These are cases in which the mixing height could not be computed since it was greater than the last standard pressure level for which observational data was available. These cases were arbitrarily assigned a value of 5000 m and are included in the statistics of mixing heights greater than 2000 m in this study. A single station (Great Falls, Montana) registered mixing heights in this category.

'Cold advection' cases (C) are defined as conditions in which the mid-afternoon surface temperature is less than the surface temperature of the 1200 GMT temperature profile. In these cases, the mixing depth (and corresponding mean wind speed) cannot be computed. These cases were identified and isolated in the frequency calculations. Although they are not included in the frequency tables in the current study, this deletion should not seriously hamper the results in the southern regions (Chapters 1-8) where annually only around 5% of the total cases are C-type (see following table). However, for northern regions (Chapters 9-11) and the High Arctic region (Chapter 12) 'cold advection' cases average around 10% and 20%, respectively. A considerable number of these cases occur in winter during the polar night when diurnal cooling near the surface may not be due to advection but rather radiational cooling. Further investigation of the application of the mixing depth statistics to regions north of latitude 60°N is currently underway.

Missing cases (M) are significant (i.e., around 10% or more of the total sample) at the stations marked * on the following table. All M cases have been deleted from the total sample in the frequency computations in this study.

Number Frequencies of U-, C- and M- type Cases
(for each rawinsonde station in the study).

REGIONS	M	C	U	% C-type
1. Pacific:				
Port Hardy	19	39	0	3%
2. Rockies:				
Spokane	20	32	0	2%
Prince George	30	60	0	4%
Whitehorse	19	119	0	8%
3. Lee of the Rockies:				
Great Falls	26	77	7	5%
*Glasgow	124	70	0	5%
Edmonton	16	61	0	5%
4. Prairies:				
Bismarck	22	57	0	4%
The Pas	10	104	0	7%
5. Great Lakes:				
Flint	24	55	0	4%
International Falls	26	72	0	5%
Sault Ste Marie	14	76	0	5%
Buffalo	49	82	0	6%
Green Bay	21	60	0	4%
Maniwaki	28	70	0	5%
6. Appalachians:				
Caribou	20	37	0	3%
Albany	31	44	0	3%
7. Atlantic:				
*Argentia	760	79	0	6%
*Stephenville	263	83	0	6%
Sept Isles	76	50	0	3%
Sable Island	20	105	0	7%
8. Central Quebec-Labrador:				
Goose	44	55	0	4%
*Nitchequon	271	97	0	7%
9. Mackenzie Valley:				
Fort Smith	12	119	0	8%
Fort Nelson	20	98	0	7%
Norman Wells	20	151	0	10%
Inuvik	10	218	0	15%

REGIONS	M	C	U	% C-type
10. Hudson Bay:				
Trout Lake	34	95	0	7%
Moosonee	39	94	0	6%
Churchill	30	171	0	12%
Baker Lake	47	166	0	11%
Coral Harbour	52	119	0	8%
*Inoudjouac	86	174	0	12%
11. Baffin:				
Clyde	63	198	0	14%
Frobisher Bay	22	150	0	10%
*Fort Chimo	250	115	0	8%
12. High Arctic:				
Sachs Harbour	9	301	0	21%
Coppermine	12	289	0	20%
Hall Beach	15	209	0	14%
Resolute	53	238	0	16%
*Mould Bay	166	309	0	21%
Isachsen	39	309	0	21%
Eureka	21	330	0	23%
Alert	53	496	0	34%

APPENDIX F

APPENDIX F

ATMOSPHERIC AREAS OF THE UNITED STATES

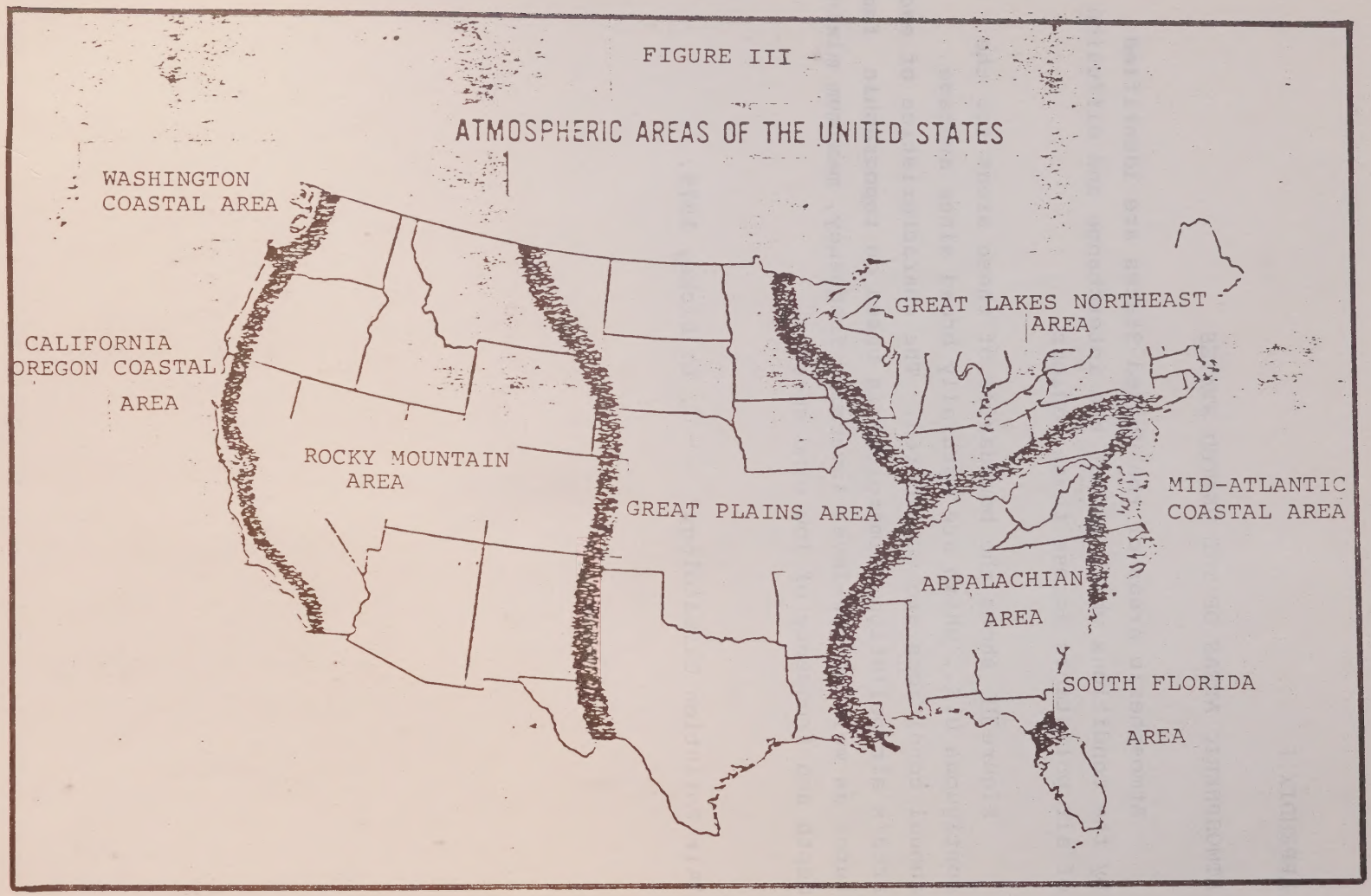
Atmospheric areas of the United States are identified by the conditions which affect the interchange and diffusion of air pollutants across these regions.

Figure III shows the boundaries of these areas for the contiguous U.S., which are naturally broad since average annual conditions are considered. The characteristics of each area's air pollution climatology is based on topographic features as well as low-level inversion frequency, maximum mixing depth and frequency of low wind speeds.

"Air Pollution Climatology" - J. L. Dicke, 1975.

FIGURE III

ATMOSPHERIC AREAS OF THE UNITED STATES



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Regional frequency distributions

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